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Into Space!

At last the long-awaited announcement has been made that West Germany has agreed in principle to participate in a European organization for the development of space vehicle launchers. Essentially, this announcement means that Germany has accepted the Anglo-French proposals for constructing a three-stage rocket incorporating a modified Blue Streak as first stage and a French liquid-propelled rocket (not the Véronique or Supervéronique) as the second. Britain would bear one-third of the cost, France nearly one-quarter, and Germany about one-fifth, the balance being contributed by other nations, whom it is hoped will now follow Germany's example.

There will be some who will maintain that Germany's participation has been obtained at too high a price, and that it would have been better if Britain and France—or even just Britain—had decided to "go it alone". They will support this view by pointing out that Germany has apparently been able to insist on at least three conditions for her entry into the "Space Club"—first, that the share of German industry in the third stage of the vehicle should be substantial; second, that German industry should also participate in the research and development work that still remains to be done on the first and second stages of the proposed vehicle, and third, that other space programmes should also be investigated.

We could not agree with such objections, for these reported—and unconfirmed—conditions seem reasonable enough, provided they are properly interpreted. Throughout the long waiting period it has been taken almost for granted that Germany would be responsible for the third stage—in the first venture of a co-operative organization it was obviously desirable that it should be built by a country other than Britain and France, for they already were undertaking major parts of the project. Her industrial potential and past experience in rocket technology made it inevitable that Germany would be thought of in this way—although had things not turned out the way they did there were other European nations quite capable of designing and building the proposed third stage.

The second condition is certainly welcome in theory: German engineers and scientists should be able to make a useful contribution to any technical project. Moreover, as partners in the organization they must have access to the documents and information concerning the other sections of the work. Equally, Britain and France must have access to the German work—in fact, this condition must be general in its application and all participating countries must have equal rights in

this respect, although their financial and technological contributions may differ. How this will work in practice remains to be seen.

As for the third proviso, we enthusiastically support the suggestion that other space programmes should be investigated. One intention seems to have been that the use of American vehicles as bottom stages should be considered—if the whole vehicle were to be of American manufacture there would be little left for the proposed European organization to do, for research satellites are the responsibility of a separate research organization already in existence (G.E..E.R.S. or E.S.R.O.); that leaves only the occasional communications or navigation satellite for E.S.L.O. (European Space Launcher Organization), as the new body has been named provisionally.

The immediate task of E.S.L.O. must be to press ahead with the design and construction of the proposed three-stage launcher based upon Blue Streak—and here we would like to see a more vigorous programme than is apparently envisaged. Nothing must stand in the way of this objective but if additional men and money can be made available, E.S.L.O. should certainly take advantage of any suitable offers of American boosters for incorporation in launching vehicles.

The third proviso is capable of a wider interpretation, however: it can be taken to mean that more advanced launchers should be developed by the proposed organization. That is how we read it and that is why we support the proviso with enthusiasm. Like any other body, E.S.L.O. must either progress or die, and although it has not yet been officially established we can express the hope that right from the start of its existence it will be thinking ahead and planning a long and varied programme to follow the Blue Streak launcher. Ultimately this should include the building of manned space vehicles.

The planning of the future programme can only be undertaken as a joint activity: the participating nations cannot be expected to rubber-stamp their approval on plans drawn up by a single member, no matter how excellent these plans may be. As this means that any advanced studies now being undertaken by individual nations may well have to be scrapped or modified, we hope that the political preliminaries will not be unduly protracted.

We are glad to note that in parallel with this action at government level, there has been a move by industry in Western Europe to establish an international body to deal with space matters. Such associations must be expected in many fields now that Britain and other European Free Trade Area countries seem likely to join the European Common Market; this particular body will be especially important.

Happily, a closer link with the continent is also being achieved at Society level; evidence of this was provided by two very successful meetings held towards the end of June: the Colloquium on Sounding Rockets held in Paris and organized by the Société Française d'Astronautique, with the collaboration of Associazione Italiana Razzi and the B.I.S., and the First European Symposium on Space Technology which we organized in London with considerable assistance from the French society. This co-operation is to be continued by holding joint meetings in London and Paris each year, and in particular, by the S.F.A. undertaking the organization of the Second European Symposium, in France in 1962. B.I.S. assistance will include the provision of papers for the meeting. We hope that subsequent symposia may be held in Germany or other countries belonging to E.S.L.O.

G. V. E. THOMPSON.

A PRELIMINARY STUDY OF THERMONUCLEAR ROCKET PROPULSION*

By J. REECE ROTH,† S.B., Member

ABSTRACT

This paper investigates the feasibility of applying controlled thermonuclear power to rocket propulsion. Such application is shown to be possible within the existing framework of knowledge of thermonuclear processes. The limiting values of reaction temperature, particle density, plasma volume, and power output are derived from theoretical and practical considerations. Relationships are derived which predict the size, mass, thrust, specific impulse, and mass flow of thermonuclear rocket engines. All parameters of interest are calculated for two hypothetical thermonuclear rocket engines, the smaller of which operates near the minimum practical power output, and the larger of which operates at the maximum practicable power density. It is shown that thermonuclear rockets cannot operate in a planetary atmosphere, and that their thrust-to-mass ratio must necessarily be of the order of $10.^{-4}$ The advantages and limitations of thermonuclear rocket propulsion are discussed, and it is examined as a possible means of interstellar flight.

I. INTRODUCTION

THERMONUCLEAR reactions consist of the fusion of two light element nuclei. These reactions form an attractive basis for rocket propulsion because of the high energy content of thermonuclear fuels. The fusion process results in a small loss of mass, which appears as kinetic energy of the reaction products. The energies required to fuse light nuclei are of the order of thousands of electron volts. Shechtman and Larisch[1] have shown that these energies preclude the use of material walls to confine a reacting plasma, and that external fields are therefore required. Confinement by a magnetic field is the only practicable method on a laboratory scale. The magnetic bottle is among the most promising methods of magnetic confinement, and is best suited for thermonuclear rocket propulsion. A magnetic bottle consists of an axially symmetric magnetic field like that shown in Fig. 1. The plasma is confined in the region of lesser

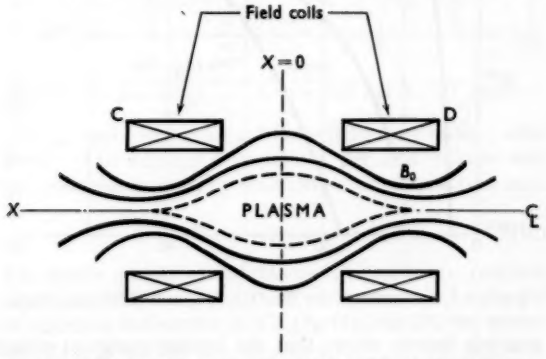

FIG. 1. Schematic of a magnetic bottle for the confinement of a thermonuclear plasma.

magnetic field strength between the field coils. The experiments performed to date use a magnetic field configuration that is symmetrical about both the axis and the midplane, $X = 0$. By making the field strength at one end of the magnetic bottle greater than that at the other, it is possible to make the plasma escape preferentially from one end of the bottle. The charged reaction products that escape in this way may be used as a rocket exhaust. One may refer[2] to the confining ability of a magnetic field as a magnetic pressure, p_m, on the plasma. In a magnetic bottle, the magnetic pressure will be approximately equal to the material pressure, p_a:

$$p = B^2/2\mu_0 = nkT \text{ joules/m}^3. \quad .. \quad .. \quad .. \quad (1a)$$

$$B = \sqrt{2\mu_0 nkT} \text{ webers/m}^2 \; .. \quad .. \quad .. \quad (1b)$$

The reactions of interest for thermonuclear power production are those between two deuterons (DD), and a deuteron and a triton (DT). The consideration which narrows down the choice of thermonuclear fuels is bremsstrahlung radiation from the reacting plasma. It is obvious that a self-sustaining reaction must radiate no more power than is produced by thermonuclear reactions. In general, the reactions with the highest cross sections have the lowest critical energies. According to Post,[3] the critical energy for the DT reaction is about 5 keV., and is 35 keV. for the DD reaction. The critical energies of other possible reactions, such as those involving lithium, are much higher. The power required to maintain a confining magnetic field is directly proportional to the kinetic temperature of the plasma. The power required to confine thermonuclear reactions involving lithium or any of the heavier elements would be prohibitive. For this reason, only the DD and DT reactions are considered in this paper.

The DD reaction can give rise to two sets of reaction products, which are produced with about equal probability. These two reactions are given below, and include the energy carried away by each reaction product. They are collectively referred to as the DD reaction.

$$D + D \rightarrow (^3He + 0{\cdot}82 \text{ MeV.}) + (n + 2{\cdot}46 \text{ MeV.}) \quad (2)$$

$$D + D \rightarrow (T + 1{\cdot}01 \text{ MeV.}) + (p + 3{\cdot}02 \text{ MeV.}) \quad (3)$$

The ^{3}He and T will react with the deuterium to yield further energy,

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$$D + T \rightarrow (^4He + 3{\cdot}52\ MeV.) + (n + 14\ MeV.) \quad (4)$$

$$D + {}^3He \rightarrow (^4He + 3{\cdot}67\ MeV.) + (p + 14{\cdot}7\ MeV.) \quad (5)$$

Equation (4) is the DT reaction, If the initial energy of the T and ^3He are taken into account, the overall reaction becomes

$$6D \rightarrow (2n + 17{\cdot}27\ MeV.) + (2^4He + 7{\cdot}55\ MeV.) + (2p + 18{\cdot}38\ MeV.) \quad (6)$$

In this paper, the above reaction will be referred to as the *supplemented* DD *reaction*. A total of 43·20 MeV. is released upon the reaction of six deuterons. 60% of this energy remains in the plasma with the charged particles, and 40% is carried away by neutrons.

At least four criteria determine the best thermonuclear reaction for rocket propulsion. These include the ease with which the reacting plasma may be magnetically confined, the average energy released per reaction, the proportion of the energy released which remains with the reaction products in the plasma, and the availability of the fuel.

The critical energy of the DT and the supplemented DD reactions are, respectively, 5 keV. and 10 keV. The DT reaction is to be preferred by the first criterion, since it will require only about half as much power for confinement as the supplemented DD reation. From Eq. (4) and (6), the supplemented DD reaction is seen to produce 14·4 MeV. per reacting pair, while the DT reaction yields 17·5 MeV. For application of thermonuclear power to rocket propulsion, as much energy as possible should remain with the charged reaction products, since this energy may be converted directly into thrust without undergoing the losses associated with some type of Carnot conversion process. The energy carried away by neutrons and radiation must be recovered as heat. A large fraction of this heat energy will be lost in being converted into electrical power, or some other form of energy. The supplemented DD reaction is superior to the DT reaction by the third criterion since, respectively, 60% and 20% of the energy released remains in the plasma in the form of charged reaction products.

The supplemented DD reaction is to be preferred by the fourth criterion, because deuterium is naturally available in large quantities, whereas tritium is not. Tritium must be artificially produced, at great cost. If deuterium were used, it should be possible to refuel a thermonuclear spaceship at any planet where water or hydrocarbons are found, since the proportion of deuterium in hydrogen is presumably constant throughout the universe. The above considerations lead this author to choose the supplemented DD reaction for application to thermonuclear rocket propulsion.

II. STEADY-STATE CONDITIONS WITHIN A THERMONUCLEAR PLASMA

Enough information is now available to determine the optimum kinetic temperature for the reacting plasma in a thermonuclear rocket engine. Examination of Equations (2)–(5) shows that without the D ^3He reaction, the average DD reaction will produce 10 MeV., only 30% of which remains in the plasma with charged reaction products. If the D ^3He reaction occurs, 60% of the energy released remains in the plasma. An examination of the cross sections in Fig. 2, in addition to the analysis below, shows that the lowest energy at which the D ^3He reaction may be utilized is about 40 keV. Since the power lost by radiation goes up with increasing kinetic temperature, the lowest possible kinetic temperature should be used. A kinetic temperature of 40 keV. will therefore be assumed during the remainder of this analysis.

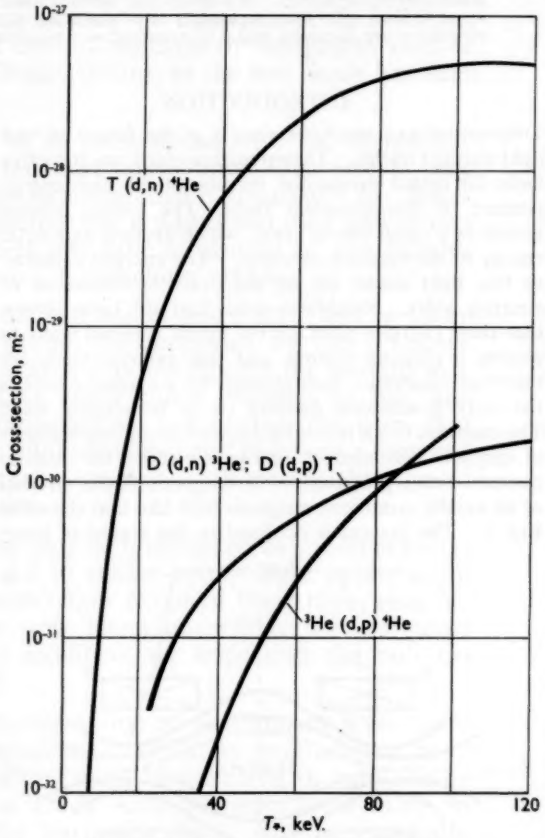

FIG. 2. Cross sections for the DD, DT, and D ^3He reactions.

The equilibrium equations for a thermonuclear plasma in which the DD, DT, and D ^3He reactions occur are given by Rose.[4] These equations are reproduced below. α is the probability of the DD reaction producing tritium, and is approximately $\frac{1}{2}$. The factors of $\frac{1}{2}$ present in the equations are necessary to prevent counting the same particle twice. S is the external source of each component.

$$\frac{dn_D}{dt} = S_D - n_D^2 \langle\sigma v\rangle_{DD} - n_D n_T \langle\sigma v\rangle_{DT} - n_D n_{^3He} \langle\sigma v\rangle_{D\,^3He} \quad (7)$$

$$\frac{dn_T}{dt} = S_T + \tfrac{1}{2}\alpha n_D^2 \langle\sigma v\rangle_{DD} - n_D n_T \langle\sigma v\rangle_{DT} \quad .. \quad (8)$$

$$\frac{dn_{^3He}}{dt} = S_{^3He} + \frac{1-\alpha}{2} n_D^2 \langle\sigma v\rangle_{DD} - n_D n_{^3He} \langle\sigma v\rangle_{D\,^3He} \quad (9)$$

Fig. 2 lists the cross sections for the above reactions, after Arnold *et al.*,[5] and Fig. 3 shows the quantities

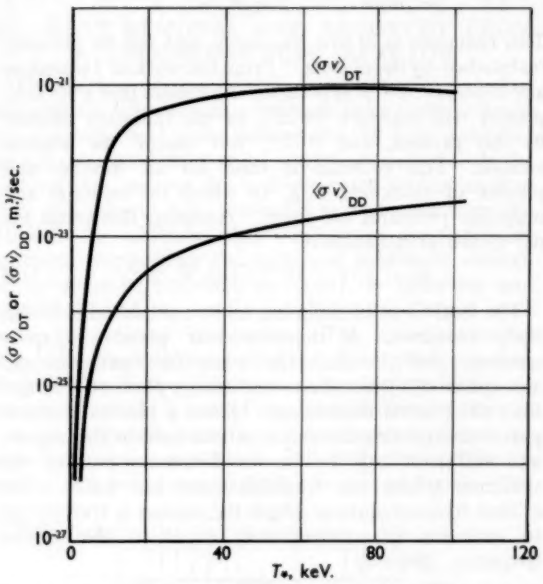

FIG. 3. The parameter $\langle\sigma v\rangle$ for the DD and the DT reactions.

$\langle\sigma v\rangle_{DD}$ and $\langle\sigma v\rangle_{DT}$ for a Maxwellian distribution, after Post.[3] The number of reactions per unit volume and per unit time is given by the thermonuclear reaction rate, R.

$$R = n^2 \langle\sigma v\rangle \text{ reactions/m.}^3\text{-sec.} \quad .. \quad (10)$$

The power density of the plasma is equal to the reaction rate times the energy released per reaction. In the set of reactions considered in Eq. (7), (8), and (9), the power density is given by

$$p_D = \tfrac{1}{2} n_D^2 \langle\sigma v\rangle_{DD} W_{DD} + n_D n_T \langle\sigma v\rangle_{DT} W_{DT} + n_D n_{^3He} \langle\sigma v\rangle_{D\,^3He} W_{D^3He} \text{ W./m.}^3 \quad (11)$$

If Eq. (7), (8) and (9) are considered in the steady state ($dn_D/dt = dn_T/dt = dn_{^3He}/dt = 0$) in which there are no external sources of tritium or ^{3}He, ($S_T = S_{^3He} = 0$), the power density may be set equal to

$$p_D = \tfrac{1}{2} n_D^2 \langle\sigma v\rangle_{DD} [W_{DD} + \tfrac{1}{2} W_{DT} + \tfrac{1}{2} W_{D\,^3He}] \text{ W./m.}^3 \quad .. \quad (12)$$

At an energy of 40 keV., we see from Fig. 3 that $\langle\sigma v\rangle_{DD} = 10^{-23}$ m.³/sec. Upon substitution of the energy released per reaction, Eq. (12) becomes

$$p = 1{\cdot}73 \times 10^{-35} n_D^2 \text{ W./m.}^3 \quad .. \quad (13)$$

Equation (13) allows one to estimate the deuterium density by setting the power density between limits that are suggested by practical considerations. It will be shown later that below 120 MW./m.³ not enough power is produced by the plasma to supply the confining magnetic field coils. The problem of heat transfer to the walls becomes acute above a power density of 1200 MW./m³. By comparison, a conventional rocket engine develops about 10,000 MW./m.³ If these power densities are substituted into Eq. (13), one finds that the corresponding limits of the deuterium density are $2{\cdot}63 \times 10^{21}$ and $8{\cdot}33 \times 10^{21}$ deuterons/m.³ This region of operation is shown on Fig. 4.

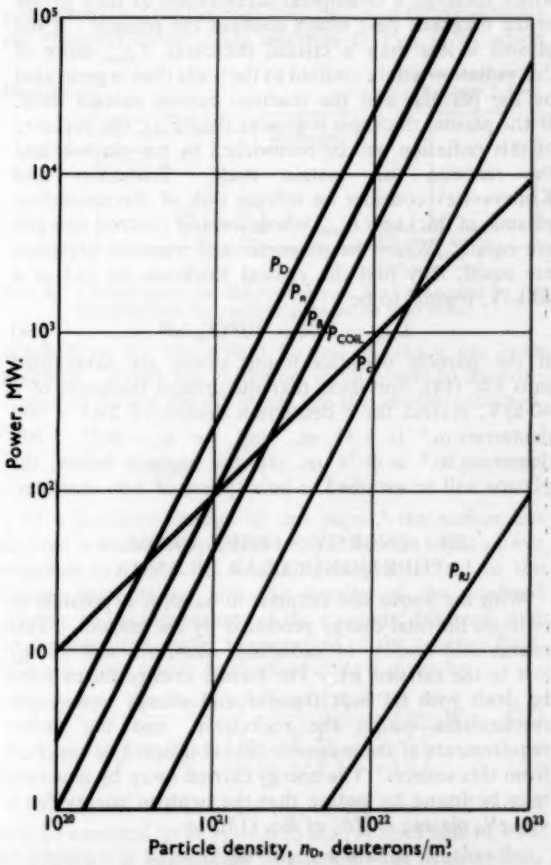

FIG. 4. Power production and losses from a thermonuclear reactor, 3 m. in diameter as a function of deuterium density, for a constant plasma kinetic temperature of 40 keV.

The above discussion applies only to steady-state operation, and it remains to consider the starting and shut-down transients of a thermonuclear rocket engine. Stopping a controlled thermonuclear reaction should be easily accomplished by shutting off the flow of deuterium, or turning off the magnetic field which confines it. Bringing the energy of the thermonuclear plasma up to

the point of net power production will be the most difficult technical problem to be surmounted before thermonuclear power can be applied to rocket propulsion. There are many promising approaches to this problem, perhaps the best of which is the DCX device at Oak Ridge. Despite much progress to date, it may require as long as 20 years to develop a fusion reactor capable of producing net power.

Unlike chemical rocket engines, there is a critical reactor size below which the thermonuclear reaction cannot sustain itself. The theory has been developed by Trubnikov and Kudryavtsev.[6] This limitation of reactor size arises from radiation emitted by electrons, which undergo a centripetal acceleration as they gyrate in the magnetic field which confines the plasma. If the plasma is less than a critical thickness, L_{min}, more of this radiation will be emitted to the walls than is generated by the plasma, and the reaction cannot sustain itself. If the plasma thickness is greater than L_{min}, the majority of this radiation will be reabsorbed by the plasma, and the reaction can sustain itself. Trubnikov and Kudryavtsev consider an infinite slab of thermonuclear plasma, of thickness L_{min}, whose ion and electron energies are equal. When the magnetic and material pressures are equal, they find the critical thickness (in m.) of a 40-keV. plasma to be

$$L_{min} = 1{\cdot}06 \times 10^{10}(T_*/n)^{\frac{1}{2}} \quad .. \quad (14)$$

If the particle densities found above are substituted into Eq. (14), one finds that the critical thickness of a 40-keV. plasma for a deuterium density of $2{\cdot}63 \times 10^{21}$ deuterons/m.^{3} is 1·31 m., and for $n_D = 8{\cdot}33 \times 10^{21}$ deuterons/m.^{3} is 0·74 m. In the analysis below, the plasma will be assumed to be a sphere of 3 m. diameter.

III. ENERGY LOSSES FROM A THERMONUCLEAR PLASMA

With the above size estimate in hand, it is possible to estimate the total energy produced by the plasma. This energy will consist of radiation, neutrons, and energy lost to the exhaust jet. The former energy fluxes must be dealt with by heat transfer and energy conversion mechanisms within the rocketship, and the power requirements of the magnetic field coils must be supplied from this source. The energy carried away by neutrons may be found by noting that the neutron energy for a 40-keV. plasma is 40% of Eq. (13), or

$$p_n = 6{\cdot}9 \times 10^{-13} n_D^2 \langle \sigma v \rangle_{DD}$$
$$= 6{\cdot}9 \times 10^{-36} n_D^2 \text{ W./m.}^3 \quad .. \quad (15)$$

The energy lost by the plasma in the form of bremsstrahlung radiation is given by Spitzer.[2]

$$p_B = \left(\frac{2\pi kT}{3m_e}\right)^{\frac{1}{2}} \cdot \frac{e^6 Z^3 n_D^2}{6\pi^2 \epsilon_0^3 h m_e c^3}$$
$$= 4{\cdot}8 \times 10^{-37} Z^3 n_D^2 T_*^{\frac{1}{2}} \text{ W./m.}^3 \quad .. \quad (16)$$

All bremsstrahlung radiation will escape from the plasma, since it is emitted in the high-frequency end of the spectrum, and its mean free path for absorption is much greater than the plasma dimensions.

The amount of energy lost as cyclotron radiation from the gyrating electrons cannot be ignored. If one starts from the usual expression for cyclotron radiation,[7] and integrates it over a Maxwellian distribution of energies and over the number of particles, one will obtain the following expression for power from this source:

$$p_C = \frac{e^4 B^2 n_e k T}{3\pi\epsilon_0 m_e^3 c^3}\left(1 + \frac{5}{2}\frac{kT}{m_e c^2} + \ldots\right) \text{W./m.}^3 \quad (17)$$

This radiation is of low frequency, and will be partially reabsorbed by the plasma. From the work of Trubnikov and Kudryavtsev[6] it is possible to estimate that a 40-keV. plasma will reabsorb 99·22% of the radiation emitted by this process, and 0·78% will escape the plasma volume. This estimate is valid for an infinite slab plasma of thickness L_{min}, in which the material and magnetic pressures are equal. Adopting this value, the net cyclotron radiation is,

$$p_C = 2{\cdot}32 \times 10^{-40} T_*^2 n_D^2 \text{ W./m.}^3 \quad .. \quad (18)$$

The final form of radiation to be considered is blackbody radiation. A thermonuclear plasma is quite tenuous, and therefore the mean free path for the absorption of all but the lowest energy photons is longer than the plasma dimensions. Since a plasma is transparent to high frequencies, it cannot emit in this region, and will emit only in the low-frequency end of the spectrum where the Rayleigh-Jeans law holds. The critical frequency above which the plasma is transparent to radiation is approximately equal to the plasma frequency, given by

$$\nu_p = \frac{e}{2\pi}\sqrt{\frac{n_D}{m_e\epsilon_0}} \text{ c./sec.} \quad .. \quad .. \quad (19)$$

The Rayleigh-Jeans law states that the amount of power radiated between 0 and ν_p cycles per second is equal to

$$p_{RJ} = \frac{e^3 k T n_D^{3/2}}{12\pi^2 c^2 m_e^{3/2} \epsilon_0^{3/2}} = 2{\cdot}67 \times 10^{-30} T_* n_D^{3/2} \text{ W./m.}^2 \quad (20)$$

In Table I is listed the power produced and lost by the various mechanisms considered above for a spherical

TABLE I.—*Power Production and Losses from a Thermonuclear Reactor*

Power density	120 MW./m.^{3}		1200 MW./m.^{3}	
	MW./m.^{3}	Total MW	MW./m.^{3}	Total MW
P_D power produced ..	120	1700	1200	17,000
P_n neutron losses ..	48	676	480	6760
P_B bremsstrahlung losses	21	296	210	2960
P_c cyclotron losses ..	2·6	36·6	26	366
P_{RJ} blackbody losses ..		0·4		2·3
Net remainder for propulsion		690		6890

plasma 3 m. in diameter, at a kinetic temperature of 40 keV., and for two power densities. Table I shows that 40% of the energy produced is available to the exhaust jet. At 40 keV., this fraction is nearly independent of the power density, because all losses except blackbody radiation are proportional to n_D^2. The remaining 60% of the power produced must be absorbed by the surrounding walls, transferred to a cooling fluid, and part of it used to maintain the magnetic field. The recovery of this heat energy is treated in the next section.

IV. HEAT REMOVAL AND RECOVERY FROM A THERMONUCLEAR REACTOR

The reacting plasma must be furnished with a mechanism which will provide a vacuum-tight surface, house the magnetic field coils, remove the i^2R heat generated by the magnetic field coils, attenuate and absorb the neutron flux, remove the heat generated by the neutron flux, and remove heat generated by radiation from the plasma. In addition, this mechanism must provide structural support for the walls and field coils, enough energy must be recovered to supply the spaceship and field coils, and the heat rejected by the Carnot cycle must be radiated into space. The entire assembly should be simple in design, and as lightweight as possible. Perhaps the most satisfactory design for application to rocket propulsion is a novel one, which is described below.

It is proposed that the thermonuclear plasma be surrounded by a multi-layer coil of hollow refractory tubing, in a configuration similar to that of Fig. 5. The

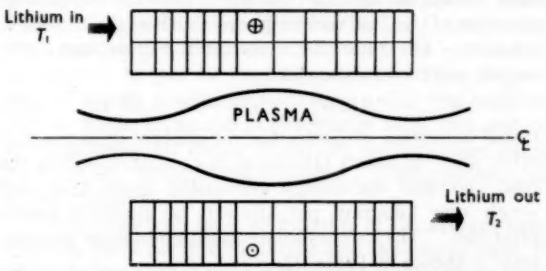

FIG. 5. Cross-sectional view of the confining coils for a thermonuclear plasma. Note the decreased coolant passage thickness (and hence increased current density) near the magnetic mirrors.

turns of this coil should be tightly wound, so that the surface facing the plasma will be smooth and vacuum tight. Liquid lithium can be made to flow through this coil of hollow tubing. It can be introduced at a temperature above its melting point, circulate through the tubing, and absorb the heat transferred through the inner wall. This flowing lithium will moderate the neutron flux, absorb the heat generated thereby, and eventually reach a desired high temperature, T_2. A radial thickness of one metre of natural lithium should be sufficient to moderate essentially all neutrons.

The current necessary to generate the magnetic field will flow through the lithium, which is an electrical conductor. The flow of current can be maintained by a suitable potential impressed across the inlet and outlet ports. The varying magnetic field strength required to form a magnetic bottle may be produced by varying the axial width of the cooling passages. An important advantage of this proposal is that the i^2R losses required to maintain the magnetic field may be partially recovered, along with the heat generated by the thermonuclear rocket motor.

After leaving the cooling jacket, the liquid lithium could be pumped to an energy conversion mechanism, which would either convert the heat into electricity thermoelectrically, or generate electricity by means of a heat exchanger, turbine, and generator. The net input power required for the coils may be found by considering the thermodynamic cycle outlined in Fig. 6, in which

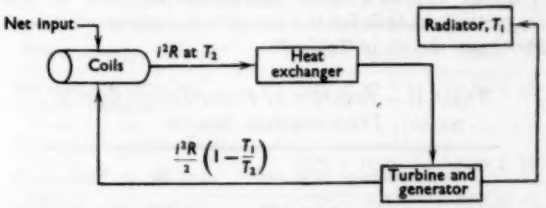

FIG. 6. Carnot cycle for the recovery of heat generated by i^2R losses within the confining magnetic field coils.

one-half of the theoretical Carnot efficiency has been assumed. From Fig. 6, the net input power to the coils is seen to be just the i^2R losses less the amount returned, or

$$P_{\text{COIL}} = \frac{i^2R}{2}\left(1+\frac{T_1}{T_2}\right) \text{W.} \qquad .. \quad (21)$$

In a previous version of this paper,[8] the author has derived a relationship which relates the net input power required to produce a confining magnetic field to the kinetic temperature and the density of the confined plasma, to the dimensions of the magnetic field coil, and to the inlet and outlet temperature of the cooling fluid. The net input power to the field coils is given by

$$P_{\text{COIL}} = \frac{4\pi e V n_D \Omega (r_2^2 - r_1^2)(T_1+T_2)}{\mu_0 L N_R T_2 \left[\ln\left(\frac{r_2+\sqrt{x_0^2+r_2^2}}{r_1+\sqrt{x_0^2+r_1^2}}\right)\right]^2} \text{W.} \qquad (22)$$

The plasma radius is 1·5 m., so the inner coil radius will be assumed to be $r_1 = 1{\cdot}75$ m. A thickness of 1 m. of lithium will be required to attenuate the neutron flux, resulting in an outside coil radius of $r_2 = 2{\cdot}75$ m. A coil length of $L = 7$ m. should be sufficient to confine the plasma, and $x_0 = L/2 = 3{\cdot}5$ m. Fabrication of the coils will be excessively difficult if the number of turns along the radius is too large, and therefore $N_R = 12$ will be chosen as a working number. The low-temperature heat sink of the Carnot cycle should not operate at a temperature so low that an excessively large radiating surface is required. A temperature of $T_1 = 600°$ K. is probably the lowest acceptable value.

The outlet temperature of the lithium, T_2, will be limited by the boiling point of lithium, 1600° K. An outlet temperature $T_2 = 1200°$ K. will therefore be assumed. The electrical resistivity of the lithium at a mean temperature of 900° K. is found by extrapolating existing data to be[9] $\Omega = 10^{-6}$ ohm-m. For a 40-keV. plasma confined in a coil of the above properties, Eq. (22) becomes

$$P_{\text{COIL}} = 2{\cdot}29 \times 10^{-15} n_{\text{D}} T_{*} \text{ W.} \quad .. \quad (23)$$

One may infer with the help of the above equation why high power densities are required of the plasma. The power output from the plasma is proportional to n_{D}^2, whereas the power required to supply the coils is proportional to n_{D}. The point at which enough power is produced to confine a 40-keV. plasma 3 m. in diameter is about 120 MW./m.³ The power required by the magnetic field coils for the two power densities discussed above are shown in Table II.

TABLE II.—*Recovery of Power Losses from a Thermonuclear Reactor*

Power density, MW./m.³	120	1200
Power available as heat, MW.	1009	10,100
Power radiated to space, MW.	755	7550
Electrical power available, MW.	252	2520
Power required by coils, MW.	241	763
Surplus electrical power, MW.	11	1757

According to Table II, there will be a surplus of electrical power, which allows a margin of error for the analysis. Any surplus power could be used for routine operations within the spaceship, such as radio transmission, hydroponic gardens, lighting, etc. Probably the most useful application of surplus power would be the augmentation of the thrust with auxiliary ion motors.

A few aspects of this proposed coil assembly remain to be considered. The coolant velocity in the coil is given by Eq. (24) below. P_{D} refers to the total heat output of the reactor, and N_p is the number of inlet and outlet ports, which has been assumed equal to ten. Under these conditions, the coolant velocities are

$$v = \frac{P_{\text{D}}}{N_p A \rho C_P \Delta T} = 8{\cdot}5 \times 10^{-9} P_{\text{D}} \text{ m./sec.} \quad (24)$$

These coolent velocities, for lithium flowing through passages 10^{-2} m.² in area, are shown for the two power densities under consideration in Table III.

One disadvantage of this proposal is the existence of a force on the current-carrying lithium, due to its motion through the magnetic field. However, the net force on the passage walls can be reduced or eliminated by causing the lithium to flow in opposite directions in adjacent layers of the coil.

Another problem will be the high heat transfer rate from the plasma to the liquid lithium coolant. If it is assumed that the inner wall of the coil is transparent to neutrons, and that all radiation from the plasma is absorbed by a cylindrical wall 7 m. long and 3·5 m. in diameter, the heat fluxes shown in Table III will result. The highest heat transfer rate shown, 4320 W./cm.², has been successfully dealt with by existing technology. It has been tacitly assumed that no energetic ions will strike the container walls. The extent of this particle loss, and its effect upon the walls and the heat transfer rate is unknown, and must await experimental results.

TABLE III.—*Characteristics of a Power Recovery System*

Power density, MW./m.³	120	1200
Total power available as heat, MW.	1009	10,100
Power radiated by plasma, MW.	330	3328
Coolant velocity, m./sec. ..	8·55	85·5
Heat flux on walls, W./cm².	432	4320
Coil mass, kg.	$9{\cdot}35 \times 10^4$	$9{\cdot}35 \times 10^4$
Electrical power generated, MW.	252	2520
Power required for coils, MW.	241	763
Mass of generating equipment required for field coils, kg.	$2{\cdot}41 \times 10^5$	$7{\cdot}63 \times 10^5$
Generating equipment mass for remainder of electrical power, kg.	$1{\cdot}1 \times 10^4$	$1{\cdot}76 \times 10^6$
Total mass, kg.	$4{\cdot}86 \times 10^5$	$2{\cdot}75 \times 10^6$
Total mass, lb.	$1{\cdot}07 \times 10^6$	$6{\cdot}05 \times 10^6$

A final item of interest is the mass of the field coil and generating equipment. In order to arrive at an approximate result, it has been assumed that the supporting structure of the field coil weighs as much as the lithium it contains. The total coil mass for the dimensions previously assumed is, therefore,

$$M_{\text{COIL}} = 2\pi\rho L(r_2^2 - r_1^2) = 9{\cdot}35 \times 10^4 \text{ kg.} \quad (25)$$

It will be further assumed that the coolant loop requires three times as much lithium as is contained within the coil, and that the energy conversion mechanism will weigh one kilogram per kilowatt of electrical power produced. The mass estimate based upon these assumptions is shown in Table III.

It is apparent from Table III that a thermonuclear rocket engine must be a massive device, and that nearly all of this mass consists of energy conversion equipment. The assumed value of one kilowatt per kilogram of conversion equipment is very optimistic for present technology, and it is unlikely that this estimate can be realized in the immediate future. In order to grasp the significance of these high power-plant masses, it is necessary to know the thrust, specific impulse, and mass flow relationships for a thermonuclear rocket engine. These are derived below.

V. PERFORMANCE PARAMETERS FOR A THERMONUCLEAR ROCKET ENGINE

It is well known that a charged particle in a magnetic field will gyrate in a circle of radius r; hence, by the equation of motion, the Lorentz force

$$\mathbf{F} = e(\mathbf{v} \times \mathbf{B}) = \frac{mv^2}{r} \quad .. \quad .. \quad (26)$$

In the laboratory frame of reference, these particles also move along the magnetic field lines, and their paths trace out a helix. Magnetic mirrors are so called because under certain conditions these gyrating particles, when moving in the direction of increasing magnetic field strength, will decrease and reverse their velocity along this direction. Two such magnetic mirrors which enclose the same set of magnetic field lines constitute a magnetic bottle, within which a plasma may be confined. The mechanism responsible for magnetic confinement is discussed by Spitzer.[2]

Spitzer shows that the fraction of particles which leak out of a magnetic bottle is given by the expression below,

$$R_M = B_{\min}/B_{\max} \quad .. \quad .. \quad (27)$$

He assumes an isotropic velocity distribution of particles that do not interact with one another. There exists an escape cone in velocity space of half angle θ_0, centred about velocities parallel to the magnetic field axis. The above expression is equivalent to the fraction of velocity vectors of an originally isotropic velocity distribution that fall within this escape cone. One would expect collisions to increase the number of particles lost through the magnetic mirror, since their velocity vectors will be knocked into the escape cone by such interactions.

The general form of Eq. (27) was experimentally observed to be valid by the present author.[10] Small values of R_m were observed to confine the plasma better than high values, although small values did not confine the plasma as well as Eq. (27) predicts. These experimental results justify our assumption that the particles can be made to escape preferentially from one end of the thermonuclear rocket engine, by having a large value of R_m at the "throat," and a small R_m at the opposite end of the chamber.

It is necessary to have an estimate of the average time required for a particle to diffuse into the escape cone, if one is to know how many particles leave the plasma per unit time. The best available estimate of this escape time is Spitzer's[2] "self collision time," τ_c. It is dependent upon all of the relevant parameters except the mirror ratio, R_m.

$$\tau_c = \frac{2{\cdot}8\pi\epsilon_0^2 m^{\frac{1}{2}}(kT)^{3/2}}{Z^4 e^4 n_D \ln\Lambda} = 1{\cdot}12 \times 10^{31} \frac{m^{\frac{1}{2}} T_*^{3/2}}{n_D \ln\Lambda} \text{ sec.} \quad (28)$$

The term $\ln\Lambda$ appearing in the denominator is given by

$$\ln\Lambda = \ln\left[\frac{12}{Z_1 Z_2}\left(\frac{\epsilon_0}{e}\right)^{3/2}\left(\frac{V^3}{n_D}\right)^{1/2}\right]$$
$$= \ln\left[4{\cdot}9 \times 10^{17}\left(\frac{T_*^3}{n_D}\right)^{1/2}\right] \quad .. \quad (29)$$

Values for a deuterium plasma have been substituted in the above two equations. $\ln\Lambda$ is nearly constant over the range of densities under consideration, and for a 40-keV. plasma is nearly 21. The self collision time for the plasma is shown in Table IV below for the two power densities under consideration. It is interesting to note that Eq. (28) holds true for any type of magnetic confinement. With Eq. (28) it is possible to derive the mass flow from a thermonuclear reactor,

$$\dot{M}_E = \frac{m n_D V_p}{\tau_c} \epsilon$$
$$= 8{\cdot}9 \times 10^{-32} \epsilon \frac{m^{1/2} n_D^2 V_p \ln\Lambda}{T_*^{3/2}} \text{ kg./sec.} \quad .. \quad (30)$$

The mass flow is listed in Table IV, for escaping particles with an average mass of 2 atomic mass units.

TABLE IV.—*Performance Parameters for a Thermonuclear Rocket Engine*

Power density, MW./m³	120	1200
Self-collision time, sec. ..	$2{\cdot}96 \times 10^{-3}$	$9{\cdot}36 \times 10^{-4}$
Specific impulse, lb. wt sec./lb.	140,000	140,000
Theoretical mass flow, kg./sec.	$4{\cdot}20 \times 10^{-2}$	$4{\cdot}20 \times 10^{-1}$
Corrected mass flow, kg./sec.	$3{\cdot}65 \times 10^{-4}$	$3{\cdot}65 \times 10^{-3}$
Theoretical thrust, newtons	58,200	582,000
Corrected thrust, newtons	500	5,000
Corrected thrust, lb. wt.	113	1130
Thrust-to-mass ratio for power plant	$1{\cdot}05 \times 10^{-4}$	$1{\cdot}86 \times 10^{-4}$

The specific impulse of any rocket motor is just the exhaust velocity divided by the acceleration of gravity at sea level. If it is assumed that only the degree of freedom along the reactor axis contributes to the thrust, the specific impulse is found by setting $\frac{1}{2} m v_E^2 = \frac{1}{2} kT$,

$$I_s = \frac{v_E}{g} = \frac{1}{g}\sqrt{\frac{eV}{m}}$$
$$= 1{\cdot}29 \times 10^{-9}\sqrt{\frac{T_*}{m}} \text{ lb. wt. sec./lb.} \quad (31)$$

The thrust may be found from Eq. (30) and (31),

$$F = I_s g \dot{M}_E = 1{\cdot}12 \times 10^{-39} \frac{n_D^2 V_p \ln\Lambda}{T_*} \epsilon \text{ newtons.} \quad (32)$$

It should be noted that Eq. (28)-(32) apply only to particles escaping the thermonuclear plasma.

Unlike chemical rocket engines, the thrust of a thermonuclear rocket engine does not depend on the mass of the exhaust particles, and is inversely proportional to their "combustion temperature." The factor ϵ appearing in Eq. (30) and (32) is necessary because the mass flow is not accurately given by Eq. (30), since it contains no dependence upon the mirror ratio, R_m. ϵ may be estimated by requiring the power of the exhaust jet to equal the power available from the thermonuclear plasma, given in Table I. In the present case, $\epsilon = 0{\cdot}0085$. The corrected thrust and mass flow are shown in Table IV.

VI. SUMMARY

By basing this analysis upon the best available theory of thermonuclear power production, it has been possible to demonstrate the feasibility of thermonuclear rocket propulsion, and to estimate the limiting plasma conditions under which a thermonuclear rocket engine will operate. The supplemented DD reaction was chosen for this analysis because deuterium is naturally available, relatively inexpensive, and a large fraction of the energy released by the supplemented DD reaction remains in the plasma, rather than being carried away by neutrons.

The smallest dimension of the plasma is given by Eq. (14), from the work of Trubnikov and Kudryavtsev. This dimension was assumed to be 3 m. for the conditions above, a conservative value which is larger than Eq. (14) indicates is necessary. There is no upper limit to the physical size of a thermonuclear reactor, although Eq. (22) implies that it is more advantageous to add to the length of the reactor than to its radius. The lower limit of the power density is determined by the power required for the confining magnetic field coils. For the above conditions, the plasma cannot supply enough power to confine itself below a power density of about 120 MW./m.^{3} The upper limit of the power density is determined by the maximum tolerable heat transfer to the surrounding walls. Under the assumed conditions, a power density of 1200 MW./m.^{3} resulted in an energy flux of 4320 W./cm.^{2} to the walls.

There is no definite upper limit to the kinetic temperature of the plasma, but one must keep in mind that the power required for the field coils is proportional to T_*, and the thrust is proportional to $1/T_*$. It is therefore advisable to use the lowest possible energy, 40 keV. in this instance. The limits of the particle density are related to the limits of the power density and of the plasma kinetic temperature by Eq. (13). The expressions which describe the power production and losses from a spherical plasma three meters in diameter are plotted as functions of plasma energy and density on Fig. 7 and 4, respectively.

The information provided by Tables I-IV enables one to deduce two significant limitations of thermonuclear rocket engines. The first limitation is that a thermonuclear rocket engine cannot be used for planetary takeoffs, since its thrust-to-mass ratio is much less than unity. It is very unlikely that the thrust-to-mass ratios shown in Table IV can be much improved upon for a pure thermonuclear rocket, since the thrust and the mass of the energy conversion equipment are both proportional to the power output. The expected thrust-to-mass ratio for the power plant is about 10^{-4}, although slightly higher values are possible for much larger engines. The second limitation is that a thermonuclear rocket engine cannot operate in an atmosphere. The density of the plasma will be of the order of 10^{21} particles/m.^{3}, which is to be compared to a density of $2{\cdot}5 \times 10^{25}$/m.^{3} for standard sea-level conditions. This limitation arises from the fact that atmospheric gases will be unaffected by the magnetic field, and will penetrate

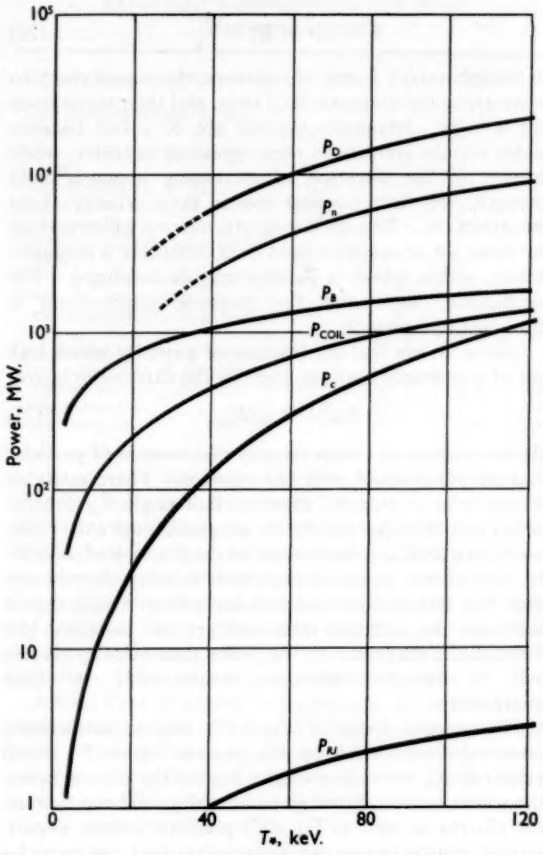

FIG. 7. Power production and losses in a thermonuclear reactor three meters in diameter at a constant deuterium density of $n_D = 5 \times 10^{21}$ particles/m.^{3}, as a function of the kinetic temperature of the plasma.

the plasma volume. Once inside the plasma volume, the gases will radiate, in the form of bremsstrahlung, Z^3 times as much energy as the deuterium. Even a fraction of 1% of such impurities will be sufficient to quench the reaction.

The reader should be warned of four weak links in the chain of analysis. These include the expression for the power lost in the form of cyclotron radiation, the expression for the mass flow from a magnetic mirror, the relation between the magnetic and material pressure in a magnetic bottle, and the feasibility of utilizing the reactions given by Eq. (4) and (5). The uncertainty associated with the power lost as cyclotron radiation is due to the difficulty of deriving the fraction of the radiated power that is not re-absorbed by the surrounding plasma. An examination of Table I reveals that the energy lost as cyclotron radiation could be a factor of ten larger than is predicted by Trubnikov and Kudryavtsev's theory, without being fatal to the analysis. It is unlikely,

however, that their theory is incorrect by so large a factor†.

The second difficulty is the relation between the magnetic and the material pressures in the plasma. In Eq. (1a) it was implicitly assumed that the plasma would be satisfactorily confined if these pressures were equal. It may be necessary for the magnetic pressure to be greater than the material pressure, for stability. Estimates of this ratio in the Geneva papers varied from a factor of one to a factor of five. If it were assumed that the magnetic pressure required were five times the material pressure, the required magnetic field and L_{min} would be increased by a factor of $(5)^{\frac{1}{3}}$, and the power required by the field coils, as well as the power lost as cyclotron radiation, would increase by a factor of 5. As consideration of Tables I and II will show, even this assumption is not fatal to the analysis, although it increases the minimum power density to about 800 MW./m.^{3}

The assumptions made in deriving the mass flow from the magnetic mirror are definitely at fault, since Eq. (30) does not include any dependence upon the mirror ratio. Such a dependence has been experimentally observed.[10] The complexity of the theory underlying these effects is such that further analysis must await experimental results. The tritium and He^3 produced by Eq. (2) and (3) may be lost from the plasma volume before they react with the deuterium. If future experimental evidence shows this to be the case, one then must make S_T and $S_{^3He}$ in Eq. (8) and (9) large enough to compensate for the loss.

Probably the worst engineering problem associated with thermonuclear rocket propulsion will prove to be getting the thermonuclear reaction started in space. Power must be supplied to the field coils and to the deuterium. If the plasma is heated to thermonuclear temperatures by a method similar to the DCX at Oak Ridge, no more than a few megawatts of power should be required to heat the plasma, compared with the tens or hundreds of megawatts required by the confining magnetic field coils. This power might be supplied by a conventional nuclear reactor, which could use the same energy conversion equipment as the thermonuclear cycle. The weight of such a reactor would be small by comparison with the thermonuclear reactor and generating equipment.

The specific impulse of a thermonuclear rocket engine is somewhat higher than one would wish for interplanetary missions. This problem was recognized by Clauser,[11] who proposed that the inner walls of the field coils be film-cooled by lithium, which would be heated and escape from the magnetic mirror in proportions that would yield a specific impulse of about 4000 lb. wt. sec./lb. This proposal will not work, because the lithium will contaminate the plasma, and its bremsstrahlung radiation is $Z^3 = 27$ times greater than that from the deuterium. From Table I it is evident that the reaction cannot sustain itself under these conditions.

The requirements of interstellar flight have been investigated by Shepherd.[12] One finds from his work that one of the critical requirements of an interstellar prime mover is a high ratio of power output to unit mass of the prime mover. A result of the present study is that this ratio, for thermonuclear rocket propulsion, is not nearly large enough to travel to the nearby stars in times of the order of a lifetime.

Thermonuclear rocket propulsion will be advantageous for interplanetary missions. The deuterium fuel is inexpensive, and the thermonuclear power plants may well prove to be comparable in size, mass, and cost to the power plants presently used in ocean-going vessels. Thermonuclear spaceships, combined with nuclear shuttle rockets, may prove to be the basis of a commercially practical system of interplanetary transportation.

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LIST OF SYMBOLS

B, B	magnetic field strength, webers/m.^{2} (1 weber/m.^{2} = 10^4 gauss).
C_p	specific heat capacity, joules/kg.-° K.
F, F	force, newtons (1 newton = 0·225 lb. wt.).
I_s	specific impulse, lb. wt. sec./lb.
L	thickness of plasma, m.
L	coil length, m.
M	mass, kg.
$\dot{M}$	mass flow, kg./sec.
N_p	number of inlet and outlet ports.
N_R	Coil turns along coil radius.
P	pressure
P_{COIL}	input power to field coil, W.
P_D	total heat output of reactor, W.
R	resistance, ohms.
R	thermonuclear reaction rate, reactions/m.^{3}-sec.
R_m	mirror ratio.
S	particle flow, particles/m.^{2}-sec.
T	temperature, ° K.
T_e	plasma kinetic temperature, keV.
V	volume, m.^{3}
V	potential difference, volts.
W	energy released by a thermonuclear reaction, joules.
X	rectangular coordinate.
Z	atomic number.
i	current, amperes.
m	mass of particle, kg.
n	particle density, particles/m.^{3}
p	power density, W./m.^{3}
p	pressure, newtons/m^2.
p_a	material pressure, newtons/m^2.
p_m	magnetic pressure, joules/m.^{3}
r	radius of circle, m.
r_1, r_2	radii of coil, m.
t	time, sec.
V, v	velocity, m./sec.
x_0	half coil length, m.

† For a recent discussion of this problem, see reference 13.

Λ term given by Eq. (29).
Ω resistivity, ohm-m.
α probability, defined in text.
θ_0 escape cone half-angle, degrees.
ν frequency, c./sec.
ρ density, kg./m.^{3}
σ reaction cross section, m.^{2}
τ_e "self-collision time," sec.
$\langle\ \rangle$ average value, taken over a Maxwellian distribution.

Subscripts

B bremsstrahlung radiation.
D deuterium.
E exhaust conditions.
^{3}He helium of atomic mass three.
R radial co-ordinate.
RJ Rayleigh-Jeans radiation.
T tritium.
c cyclotron radiation.
e electrons.
n neutrons.
p referring to the thermonuclear plasma.
min minimum.
max maximum.

Constants

c speed of light, 3×10^8 m./sec.
e electrostatic charge, $1{\cdot}6 \times 10^{-19}$ coulombs.
h Planck's constant, $6{\cdot}623 \times 10^{-34}$ joule sec.
k Boltzmann's constant, $1{\cdot}38 \times 10^{-23}$ joules/° K.
ϵ_0 a constant characteristic of the rationalized MKS system, $8{\cdot}85 \times 10^{-12}$ farads/m.
μ_0 a constant characteristic of the rationalized MKS system, $4\pi \times 10^{-7}$ henries/m.
g mean acceleration of gravity at Earth's sea level, 9·8067 m./sec.^{2}

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MINIMUM ENERGY ENTRY INTO PLANETARY PARABOLIC ORBITS*

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ABSTRACT

Velocity requirements for entry into parabolic orbits around the planets of the Solar System are determined, assuming transfer along a minimum energy semi-ellipse from Earth. The advantages of entry into satellite orbits of high eccentricity around the Giants are indicated.

In a previous note[1], the author considered the problem of minimum energy entry into circular orbits around planets, and the savings that could be achieved. In this note, the question of satellite orbits of high eccentricity is considered in terms of the limiting condition, *i.e.*, parabolic or escape orbits around the planets.

As in the previous note, the following simplifying assumptions are made. The orbits of the planets are taken as circular, concentric and coplanar. Transfer is made along a cotangential semi-ellipse.

For orbits within the Earth's orbit:

$$V_1 = \sqrt{V_E^2 + (V_P - V_0)^2} - V_E$$
$$V_2 = V_P - V_0$$

For orbits outside the Earth's orbit:

$$V_1 = \sqrt{V_E^2 + (V_0 - V_A)^2} - V_E$$
$$V_2 = V_0 - V_A$$

Where:

V_1 = velocity requirement for entry into parabolic orbit around planet at point where planet's escape (parabolic) velocity is V_E.
V_2 = velocity requirement for entry into orbit of planet, distant from planet.
V_P = velocity at perihelion of transfer semi-ellipse.
V_A = velocity at aphelion of transfer semi-ellipse.
V_0 = velocity of planet in orbit.

* Manuscript received 29 November, 1960.

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TABLE 1

	Mercury	Venus	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
y_0, miles/sec.	2·67	6·46	3·16	37·9	22·7	13·90	15·91	3·28
x, miles/sec.	6·00	1·60	1·66	3·52	3·36	2·93	2·54	2·34
y_0/x	0·445	4·03	1·905	10·77	6·76	4·74	6·27	1·40
$(z/x)_{max}$	0·353	0·88	0·755	0·96	0·93	0·89	0·93	0·68
z_{max}, miles/sec.	2·12	1·41	1·26	3·38	3·12	2·61	2·36	1·59
V_3, miles/sec.	14·34	8·69	8·78	12·29	12·72	12·75	12·55	12·40
z_{max}/V_3, %	14·8	16·2	14·3	27·5	24·5	20·5	18·8	12·8

V_3 = velocity requirement for departure from Earth's surface and entry into orbit of planet distant from planet.
y_0 = escape (parabolic) velocity at surface of planet.

For simplicity put:

$x = V_P - V_0$ (for orbits within the Earth's orbit), or
$x = V_0 - V_A$ (for orbits outside the Earth's orbit)
$y = V_E$
$z = V_2 - V_1$
Then $z = x - \sqrt{y^2 + x^2} + y$
or $z/x = 1 - \sqrt{(y/x)^2 + 1} + (y/x)$

The function z/x is plotted against y/x in Fig. 1.

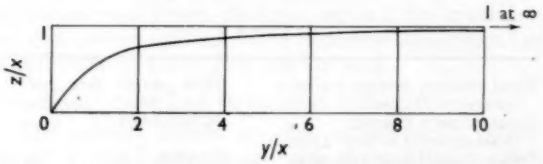

FIG. 1. Maximum saving in velocity requirement at destination resulting from entry into a parabolic orbit around the target planet, expressed as a function of the parabolic velocity (in dimensionless form).

z/x represents the proportion of the velocity change required for entry into the planet's orbit that may be saved by entering a parabolic orbit around the planet at a point where the planet's equivalent gravitational field strength relative to that velocity change is given by y/x.

Savings may always be effected in regions where z/x is positive, and this is true for all values of y/x. z/x rises steadily from 0 at $y/x = 0$, and tends to 1 as y/x tends to infinity. The higher the value of y/x, the greater the saving.

The maximum value of y is obtained at the planet's surface. It is therefore desirable to enter the parabolic orbit at a point as close to the surface of the planet as practicable, if the minimum velocity change is desired. It will be appreciated that, in contrast with the conclusions reached in the previous note, this result is completely general, and applies to all planets.

The data for the planets of the Solar System are given in Table I. The Giants, with their relatively high equivalent gravitational field strengths, give the highest values of y/x, with correspondingly high values of z/x. The velocity savings are appreciable for these planets, in the region of 2 or 3 miles/sec. The percentage savihgs, for flights starting from the Earth's surface, come out at around 20 to 25. There is thus a strong incentive to enter highly eccentric orbits around the Giants, rather than near-circular orbits, in order to reduce the velocity requirements.

Of the other planets, it will be noted that Venus appears to be suitable for application of this technique. With Mercury and Mars, these two planets are already able to benefit appreciably from the technique of entry into minimum energy circular orbits, and the advantages of entry into highly eccentric orbits are therefore less marked.

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1. S. W. Greenwood, *J.B.I.S.*, 1961–62, **18**, 73.

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SHIELDING MANNED SPACE VEHICLES FROM SPACE RADIATIONS*

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(Communication from Astra, Inc.)

ABSTRACT

The known major radiations (including primary cosmic, trapped and solar flare radiations) encountered outside the Earth's atmosphere are described. Interactions of primary cosmic radiation in the atmosphere are considered and primary cosmic radiation dose is estimated. An estimate is also made of doses accumulated in passing through the trapped radiation belts. Interactions of high-energy protons with nuclei are described, with special attention to the possible importance of the Rossi transition effect. Shielding requirements, possible materials and arrangements and difficulty of providing sufficient solar flare shielding are reviewed.

I. INTRODUCTION

WE are facing a decade in which science and technology are expected to make an enormous stride in the field of spaceflight. An important step forward has been the launching of manned space vehicles. On 1 February, 1958, the satellite *Explorer I*, in which was incorporated a geiger counter for the detection of radiation, was launched. The data first indicated the presence of intense radiation belts which have become known as Van Allen belts. Owing to the presence of these belts, a satellite orbiting through 2000–10,000 km. above the surface of the Earth would record a dose much larger than previously supposed.

To make an estimate of the radiation dose to be encountered by the personnel in a manned space vehicle and to design adequate shielding for their protection, we have to consider three contributing factors. These are the steady state values of primary cosmic radiation, the protons and electrons in the Van Allen belts, and the time variational part of the cosmic rays, the most important of which are the solar flare protons.

The inadequacy of rocket thrust as available today puts a severe restriction on the payload capacity. This limits considerably the use of massive shielding material on space vehicles. In this respect the shielding problem of space vehicles differs from that of high-energy accelerators. For space vehicles the weight of the shielding material must be optimized. The other important question pertaining to design of shielding for a space vehicle is whether a phenomenon like the Rossi transition effect would be encountered; or, that is, would there be a range of thicknesses of the shielding for which the ionization inside the vehicle would be increasing with shielding rather than decreasing.

Assigning a composite R.B.E. value‡ for the residual radiation under different thicknesses of shielding material is very important for arriving at an optimum shield. Assigning a higher permissible radiation exposure as an occupational hazard for astronauts would, of course, help in reducing the amount of shielding required.

II. PRIMARY COSMIC RADIATION

From experiments conducted with balloons and rockets it is observed that the primary radiation at the top of the atmosphere is mostly protons. Approximately 80% of the primary particles are protons and 20% are alphas. A small percentage of heavier nuclei is also present. They arrive isotropically. The average energy is approximately 4×10^9eV./particle. The energy spectrum for primary cosmic rays is given[1] by,

$$N(E) = \frac{K}{(1+E)^{3/2}}$$

where $N(E)$ = number/m.²-sec.-steradian with energy greater than E (10^9eV.), and $K = 3800$ for protons, 380 for He, 20 for C, N, O. Table I shows the relative intensities above the atmosphere at White Sands, geomagnetic latitude 41°N. (after Newell[2]).

TABLE I

Total ionizing particle intensity (range > 7·0 g./cm.²)	0·079±0·005	(sec. cm². steradian)⁻¹
Total primary intensity (Extrapolated to zero g./cm.²)	0·079±0·005	"
Proton to alpha particle ratio	5·3±1·0	
Primary proton intensity	0·058±0·005	(sec. cm.² steradian)⁻¹
Primary alpha particle intensity	0·011±0·002	"
Primary $Z > 2$ intensity	0·001±0·001	"
Albedo particle intensity ($7 \leq$ range ≤ 21 g./cm.²)	0·012±0·002	"
Electrons (< ~ 60 MeV.)	0·008±0·002	"
Slow protons	0·003±0·001	"
Slow protons or Alpha particles	0·001±0·001	"

1. COSMIC RAY INTERACTIONS IN THE ATMOSPHERE AND VARIATION OF INTENSITIES WITH ALTITUDE

Primary cosmic rays, while passing through the atmosphere (1030 g./cm.²), gradually disappear owing to their interactions with the atmosphere; at the same time secondary particles are generated. As a result of nuclear interaction the primary particle generates protons, neutrons, and π^+, π^-, and π^0mesons in the atmosphere.

* Manuscript received 15 November, 1960. Sponsored by J. Frank Coneybear, M.B.I.S.

† Astra Inc., P.O. Box 226, Raleigh, North Carolina, U.S.A.

‡ R.B.E. = Relative Biological Effectiveness (relative to a standard, *e.g.*, 200-keV. X-rays.

π^0mesons decay almost immediately to photons, which produce electronic showers. Charged π mesons decay into μ mesons, which lose energy almost entirely by ionization and then decay into electrons and neutrinos.

Cosmic rays at sea level primarily show two distinct groups; they are the soft and hard components. The soft, or electronic component, consists of electrons and photons; the hard component consists of μ mesons. The total intensity at sea level is roughly 0·1 of the primary intensity and 0·2 of this is soft.

The relative intensities of various secondary particles varies with the depth of the atmosphere. The intensity of primary cosmic ray particles decreases rapidly with the depth of atmosphere. The number of electrons and photons, however, increases with depth and goes through a maximum at about 20 km.

Electrons and photons lose energy by electromagnetic interactions, and neutrons and protons at high energy interact mainly through nuclear interactions. Nuclear interactions may be roughly divided into two parts: high-energy interactions or formation of penetrating showers (large stars) in which several pions (~140 MeV. rest mass) plus one or two nucleons may be emitted, and low-energy interactions which give evaporation stars. Evaporation stars are generated by the heating of the nucleus and as a result neutrons (E ~10–20 MeV.) and protons (E~10–30 MeV.) are boiled off.

The cosmic radiation shows the Rossi transition effect. The rate of penetrating showers in absorbers increases rapidly with thickness, up to a flat maximum at about 10 cm. of lead. The electronic component has a maximum at about 20 g./cm.^{2} of lead.

2. Dose Due to Primary Cosmic Rays

The primary cosmic ray flux according to Vernov *et al.*[3] is $\pm$ 0·1 particles/cm.^{2}-sec. In calculating doses from primary cosmic radiation the higher specific ionization and therefore higher R.B.E. for $Z > 2$ particles must be kept in mind. The unshielded dose rate for galactic cosmic rays may be accepted as 0·5 millirad/hr.; this is approximately equal to the value calculated by Schaefer.[4–7]

As mentioned earlier, the ionization due to cosmic rays goes through a maximum at about 20 km. or about 60 g./cm.^{2} On this basis we may expect that at least 100 g./cm.^{2} of shielding will be needed to reduce the dose due to primary cosmic rays below the unshielded dose. However, the dose rate due to primary cosmic rays is negligible compared with dose due to protons in the Van Allen belts and solar flare protons.

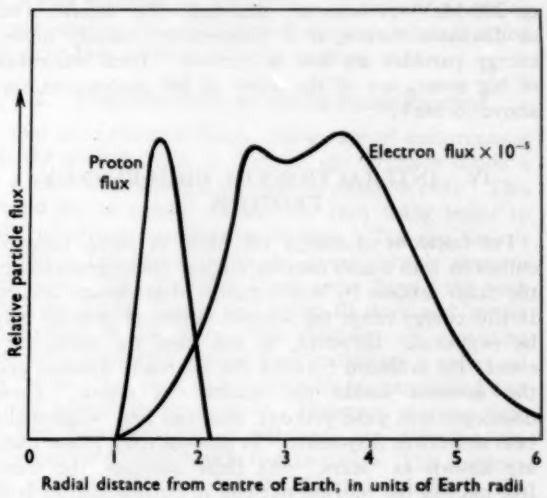
For cosmic ray particles a mean R.B.E. value of 2–5 may be applicable. Ordinarily one would expect this to be a maximum variation for R.B.E. But for the heavier ions for certain brain areas the R.B.E. values may be as large as 100; this is still an unresolved issue.

III. VAN ALLEN RADIATION BELTS AND SOLAR FLARE PROTONS

The existence of the Van Allen radiation belts was shown by the geiger counter readings of the *Explorer I* satellite. The counter was choked at 1100 km., giving an indication of intense radiation. More detailed knowledge was gathered through *Explorers III* and *IV*, Pioneer and the Luniks. The latter probes proved the existence of the outer belt. The centre of the inner zone is about 11 $\times$ 10^3 km. from the Earth's magnetic axis[8,9] and that of the second belt is centred at about 22 $\times$ 10^3 km. from the Earth's magnetic axis.[3,9–12]

1. Proton Belt

Fig. 1 shows the particle flux against the radial distance from the centre of the Earth in the equatorial plane[8,13,14].



2. The Electron Belt

The outer zone consists almost entirely of electrons with an upper energy limit of about 100 keV. Approximately 10^{11} electrons cm.$^{-2}$sec.$^{-1}$ are present at the centre of the zone. Owing to this high flux the unshielded dose would be quite high, about 10r./hr. However, it should be noted that the range for 100 keV. electrons is about 15 mg./cm.^{2} in aluminium.[15]

3. Time Variations

Time variations have been observed for protons of energy less than 10^{13}eV. (higher energy proton flux is believed to remain steady with time). These variations are related to solar conditions.[16] Important time variations may be listed as follows: (*a*) A solar diurnal variation occurs with a change of a fraction of 1%.[1] (*b*) A variation of several per cent. occurs at 27-day intervals corresponding to the solar rotational period. (*c*) A 2-5% variation has been recorded with the sunspot cycle of 11 years.[16] (*d*) A variation of up to 15% has been recorded with magnetic storms; these are known as the *Forbush decrease.*

4. Solar Flare Radiation

The solar flare protons present the maximum hazard to the personnel in a space vehicle. Solar flares may produce increases in the primary flux varying from a few per cent. to several thousand times quiescent values.[17] One unusual flare in February, 1956, produced an increase of 10^4 times the quiescent value of the 2000-MeV. flux.[18] The energy distribution of solar flare protons may be described by $3 \times 10^{13} E^{-6}$ (E in MeV.).

The frequency of flares per year reaches its maximum primarily during the years of maximum sunspot activity. Thus the most favourable periods for spaceflight would be the low solar activity periods 1963–66, 1975–77. Within a few hours of large solar flares typically 100- or 200-MeV. protons are detected. The distribution, as discussed before, is E^{-6}-dependent; usually higher energy particles are few in number. Total intensities of big events are of the order of 10^4 protons/cm.^{2}sec. above 30 MeV.

IV. INTERACTIONS OF HIGH ENERGY PROTONS

For nucleons of energy 100 MeV. or more, inelastic collisions with nuclei causing nuclear disintegrations are the main process by which energy degradation occurs. In this energy range the ionization loss of protons may be neglected. However, in this case the elementary event—the collision between the incoming nucleon and the nucleon inside the nucleus—is elastic. These disintegrations yield protons, neutrons and occasionally heavier nuclear fragments. In photographic plates these are known as "stars." At these energies, the mean free path of the moving nucleon in nuclear matter is of the order of the nuclear radius. In this case compound nucleus theory is no longer valid. We can consider the reaction to occur in two steps.

As a first step, we have the emission of one or more comparatively high-energy nucleons, including, perhaps, the incident nucleon itself. Heavier fragments may also be ejected. The number and energy distribution of the ejected nucleons depend mainly on the nucleon-nucleon scattering cross section, number of target nucleons and their kinetic energy.

As a second step we have the evaporation of nucleons from the residual nucleus. Most of the evaporated particles are neutrons, protons, and alpha-particles. The number and the energy distribution of the emitted nucleons are given by the "temperature" of the nucleus. The two-step process as described above is more likely for heavy nuclei; light nuclei will be more prone to complete break up.

With increasing energy a second type of reaction can take place in which the elementary event is inelastic. In this process a nucleon collides inelastically with another, expending part of its energy for the production of one or more charged or neutral π^0 mesons. These reactions may be represented as:

$$\begin{aligned} \mathrm{p} + \mathrm{p} &\rightarrow \mathrm{p} + \mathrm{n} + \pi^+ \\ \mathrm{p} + \mathrm{n} &\rightarrow \mathrm{p} + \mathrm{p} + \pi^0 \\ \mathrm{p} + \mathrm{n} &\rightarrow \mathrm{n} + \mathrm{p} + \pi^0 \end{aligned}$$

Knowing the rest energy of π mesons and using energy and momentum conservation laws, the threshold energy for meson production can be found. The threshold energy is given by

$$E_{\mathrm{th}} = 2m_\pi c^2 \left(1 + \frac{m_\pi}{4M}\right)$$

Using $m_\pi c^2 \cong 140$MeV. and hydrogen as target nucleus, we have $E_{\mathrm{th}} \cong 291$ MeV.

Similarly, when deuterons, helium and carbon are target nuclei, the thresholds are 209, 181, and 150 MeV., respectively.

It should be noted that the threshold for complex nucleus production is affected by the exclusion principle, the motion of the nucleons in target nucleus and the possibility of the nucleus taking a part of the momentum.

Meson production increases sharply between 400 and 800 MeV.; double meson production starts at 600 MeV., but does not become important below 1000 MeV.

Neutrons, protons and π mesons take part in nuclear interactions and the π meson has a cross section comparable to that of the nucleons. Thus with increasing energy of the nucleons, we can have not only penetrating showers, in which neutrons, protons and π mesons are generated, but we can have cascades of penetrating showers.

With the possibility of cascades of penetrating showers, the Rossi type of transition effect may be expected in which ionization under an absorber thickness may increase with addition of absorber. This effect is not expected to be pronounced below 10^4MeV.

Thus for Van Allen protons ($E < 700$ MeV.), the primary dose would be reduced by any amount of shielding. It has already been noted that the dose from "steady state" cosmic radiation increases with additional shielding (atmosphere) until a maximum is reached at 60 g./cm.^{2} It has also been noted that the dose from "steady state" cosmic radiation is negligible.

The question of whether or not solar flare radiation will exhibit the Rossi effect cannot be answered without a detailed analysis of the spectrum of the solar flare. It may be assumed that the solar flare protons of below $\sim 10^4$ MeV. in energy will be attenuated without exhibition of the Rossi effect; it may also be assumed that the proton flux above $\sim 10^4$ MeV. will exhibit the Rossi effect. Whether or not the total dose increases when a thin shield is used, therefore, depends upon the relative numbers of protons above and below $\sim 10^4$ MeV. It may be noted that the "steady state" cosmic radiation has a proton spectrum with a much larger fraction above 10^4 MeV. than the solar flare spectra. For instance[1], the flare of 23 February, 1956, increased primary cosmic radiation by a factor of 50 in the energy range of 10^3–10^4 MeV., but only by a factor of three in the energy range of 10^4–10^5 MeV.

To sum up, the reactions by high-energy particles may be put into four approximate divisions: spallation, fission, fragmentation, and secondary reactions.[19] In star or spallation reaction, nucleons or small fragments are emitted; in fission the nucleus is divided into two or more large fragments; in fragmentation chunks of nuclear matter are given off. Fragmentation is essentially a high-energy process and cannot be explained by the evaporation mechanism. The spallation products interact with nuclear matter in secondary reactions.

V. SHIELDING REQUIREMENTS OF A MANNED SPACE VEHICLE

Unless the specifications of acceptable radiation doses are changed, the shielding should be designed to reduce the dose rate to the tolerance. This poses an enormous challenge to the satellite programme with its limited payload capabilities. According to a recent recommendation of the National Committee on Radiation Protection and Measurement, the occupational exposure is to be limited to 12 rem per year and the age pro-rata dose should not exceed 5 (n–18) roentgens, where n is age in years.

According to Freden and White,[10] the unshielded dose rate at 1200 km. due to protons is about 1R./hr. This corresponds to a flux of 10^3 protons/cm.^{2}sec. At the centre of the inner belt, one would probably expect a flux 10 times as high giving a dose rate of 10r./hr. Thus the total dose accumulated will depend on the contemplated orbit. Probably it is possible to penetrate the Van Allen belts with a radiation dose of 5 r. each way. Thus the radiation belts are not a great deterrent to travellers to outer space in comparison with those orbiting below 25,000 km.

1. Shielding from Trapped Radiation

As discussed earlier, the unshielded dose rate from trapped electrons in the outer belts would be 10 r./hr. However, since the average energy of the electrons is quite low, a few g./cm.^{2} of high-Z materials at the surface of the satellite will be sufficient to stop the electrons and the accompanying bremsstrahlung. It may be noted that the high-temperature-resistant outer covering might be sufficient for this purpose.

Effective shielding against the protons in the inner belt is very difficult to achieve. The range of protons in this region is about 100 g./cm.^{2} Even if the protons are completely stopped, there will still be a rather high residual ionization due to neutrons, the end products being neutrons. The neutron production per proton increases rather steeply with proton energy. For 190-MeV. protons the following total neutron evaporation cross-sections, σ_n, and the number of evaporation neutrons per nuclear collision, n_n, have been tabulated by Gross[21] (see Table II).

Hydrogen, helium and carbon will be suitable for shielding against protons in order of preference. Obvious impracticability of using H and He indicates carbon or a hydrocarbon as the best choice. An advantage of carbon, as indicated in the preceding tabulation, is that neutron production per proton is comparatively low. A hydrocarbon may be a desirable shielding material, if compactness is not an overriding consideration, since stopping of protons and attenuation of secondary neutrons will be excellent in it.

TABLE II

Target	σ_n, 10^{-24}cm.^{2}	n_n
C	0·104 ± 0·026	0·45 ± 0·11
Al	0·86 ± 0·17	2·1 ± 0·4
Ni	1·38 ± 0·28	2·0 ± 0·4
Ag	5·17 ± 1·03	4·7 ± 0·9
Au	13·64 ± 2·7	8·0 ± 1·6

2. Shielding Against Solar Flare Protons

One of the largest flares, whose rate of occurrence is on the average once in 5 years, can produce inside a 1 g./cm.^{2} chamber a total dose of 600,000 rads. This would be, of course, lethal; 500 rads being lethal to 50% of exposed subjects in 30 days. The rise time is usually a few minutes and the decay time is about a few hours. On the other hand, some flares have been observed which persist for about 10 days and repeat themselves in 28 days. The difficulty of providing adequate protection against these radiations is enhanced by the fact that their time variability is complicated and is not completely predictable. However, the rise time of the flare intensity is adequate for allowing the personnel in a space vehicle to take cover. This suggests the construction of a heavily shielded cubicle in the space vehicle in which astronauts may take cover in case of emergency. Under a shield of 180 g./cm.^{2} of carbon, one of the biggest flares would produce a dose of 10 rads due to charged particles. There would be an additional dose due to neutrons produced in the shields of about 30 rads. It will be pertinent to keep in mind that acute radiation sickness sets in approximately at a minimum dose of 150 rem. It is difficult to provide adequate shielding against these radiations.

With the limited payloads now available to space vehicle designers, it may be necessary to design such vehicles without sufficient shielding for solar flares. Thus missions will be restricted to periods when the probability of occurrence of a solar flare is estimated to be at a minimum. Estimation of probabilities of occurrences of solar flares is frought with great uncertainties and poses a serious challenge to planners of space missions.

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THE RELATION BETWEEN HEIGHT ERROR AND ELEVATION ERROR FOR AN EARTH SATELLITE*

By K. H. FEA†, Fellow

ABSTRACT

The relation between an error in height for a satellite over the Earth's surface, and the concomitant error in elevation is determined. Various values are tabulated to assist observers and to provide a basis for weighting a set of observations.

THE determination of a satellite's height above the Earth's surface is one of the main reasons for making observations. It is desirable to investigate the dependence of elevation on height. This will enable observations to be made at elevations most sensitive to height, to yield the greatest accuracy. Conversely, elevations may be chosen which are insensitive to height errors, increasing the chances of locating the object. By evaluating this dependance, observers will be able to find the uncertainty in the apparent elevation and plan their strategy accordingly. If a number of triangulations have been made by different observers using different elevations, then the values here can be used as a basis for assigning weights to the various measures of height.

The fundamental expression used to determine the elevation, a, is:

$$\tan a = \frac{(R + R)\cos\theta - R}{(R + R)\sin\theta} \quad \ldots \quad (1)$$

Here h is the height over the Earth's surface,

R is the radius of the Earth and

θ is the great circle distance between the observer and the sub-satellite point.

By partially differentiating Eq. 1 with respect to h we find:

$$\frac{\partial a}{} = \frac{R\sin\theta}{(h + R)^2 + R^2 - 2R(R + h)\cos\theta} \quad \ldots \quad (2)$$

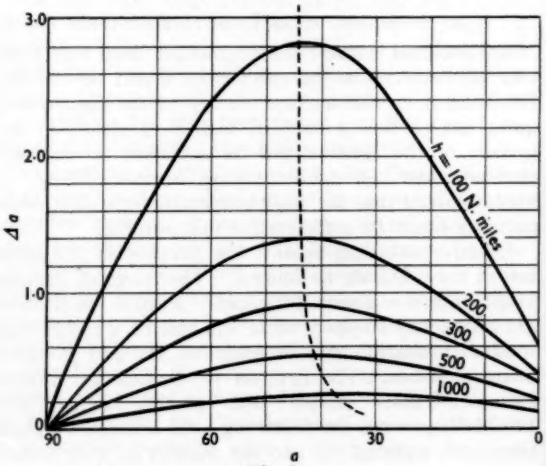

Fig. 1

* Manuscript received 18 August, 1960.

† University College, Gower Street, London, W.C.1.

TABLE I

h, N. miles	θ, degrees	a, degrees	$\frac{\partial a}{\partial h} \times 10^3$	Δa, degrees	h, N. miles	θ degrees	a, degrees	$\frac{\partial a}{\partial h} \times 10^3$	Δa, degrees
100	0·5	72·8	2·736	1·57	300	4·8	*42·6	1·597	0·92
	1·0	58·2	4·374	2·51	(*contd.*)	5·0	41·2	1·595	0·91
	1·6	*44·3	4·923	2·82		10·0	20·5	1·242	0·71
	2·0	38·4	4·902	2·81		15·0	10·1	0·921	0·53
	3·0	27·2	4·150	2·38		20·0	3·3	0·717	0·41
	5·0	15·7	2·919	1·67	500	1·0	82·2	0·235	0·13
	10·0	4·3	1·572	0·90		3·0	67·4	0·726	0·36
200	0·5	81·0	0·732	0·42		7·9	*41·1	0·932	0·53
	1·0	72·3	1·371	0·79		10·0	32·8	0·903	0·52
	2·0	57·3	2·172	1·25		15·0	19·7	0·759	0·44
	3·2	*43·4	2·429	1·39		20·0	11·0	0·624	0·36
	4·0	37·0	2·376	1·36	1000	2·0	81·2	0·118	0·07
	5·0	30·4	2·215	1·27		5·0	68·5	0·269	0·15
	10·0	12·9	1·420	0·81		10·0	50·4	0·409	0·23
300	1·0	77·7	0·639	0·36		14·5	*37·8	0·437	0·25
	2·0	66·3	1·136	0·65		20·0	25·7	0·414	0·24
	3·0	56·4	1·487	0·82		30·0	10·3	0·338	0·19
	4·0	48·1	1·571	0·90					

By differentiating Eq. (2) with respect to θ and equating to zero we obtain:

$$\cos \theta_{\text{crit}} = \frac{2R\,(h + R)}{(h + R)^2 + R^2} \quad .. \quad .. \quad (3)$$

This value of θ_{crit}, gives, when substituted in Eq. (1) the value of A_{crit}. This is the elevation most sensitive to height variation; it is marked * in Table I.

In Table I various values of h are given in nautical miles and, for these values, $\partial a/\partial h$ is given at a number of elevations. The quantity Δa indicates the change in elevation for a height error of 10 N. miles.

The tabulated figures are also shown graphically. From the curves it can be seen that the value of a_{crit} approaches 45° for low objects and departs appreciably for $h > 1000$ N. miles. The elevation becomes appreciably insensitive to error in height for $a > 80°$ and $a < 10°$.

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CORRESPONDENCE

The British Rocket Industry

SIR,

In the February issue of the *Journal*, your Editorial stated that 1961 was a year of promise for the British rocket industry.

This is so completely the opposite of the truth that I think that editorial statements of this kind come perilously close to making the Society a laughing stock. I am sure that many will agree with me that morale in all the firms is extremely low, in view of the small amount of really forward-looking research which is being undertaken, and the paucity of new projects being initiated. It is my definite impression that this outlook is by no means confined to the organizations engaged on Blue Streak, but is quite widespread throughout the industry.

We should not pretend that a state of affairs exists which is the opposite of the true—or did the Editor mean to write *promises* instead of *promise*?

Yours very sincerely,

A. V. CLEAVER.

149, Stenson Road, Derby.
2 *May*, 1961.

We sympathize with Mr. Cleaver—as Chief Engineer, Rocket Propulsion, Rolls-Royce Ltd., he will have had more than his fair share of disappointments during the last twelve months. We certainly agree with him that more imaginative research should be undertaken and that morale in the industry is bad—indeed we would go further and simply say that morale is bad in Britain—we appear to be becoming a nationa of lotus-eaters, and with governmental approval.

However, we do not regret writing that 1961 is a year of promise for the British rocket industry. Firstly, we have the excuse that the outlook was much brighter at the time the Editorial was written than when members received it several weeks later. Secondly, events in the remaining months of 1961 may yet make our statement come true. We say this partly because we are incurably optimistic and partly because we find it impossible to believe either that vacillation could continue for yet another seven or eight months or that we could write off our investment in Blue Streak and turn our backs for ever on space technology. G.V.E.T.

The British Interplanetary Society

LIMITED (by Guarantee)

SIXTEENTH ANNUAL GENERAL MEETING

NOTICE IS HEREBY GIVEN that the SIXTEENTH ANNUAL GENERAL MEETING of THE BRITISH INTERPLANETARY SOCIETY, will be held in the Lecture Hall, The Royal Aeronautical Society, 4, Hamilton Place, London, W.1, on Friday, 15 September, 1961, at 6.30 p.m. precisely for the transaction of the business specified in the Agenda below.

AGENDA

1. Report on the Society for the year ended 31 December, 1960.
2. To receive the Accounts and Balance Sheet for the period 1 January to 31 December, 1960, and the Auditors' Report thereon.
3. To consider and, if thought fit, to approve the following as SPECIAL RESOLUTIONS:
   (*a*) THAT article 5 (*b*) (concerning Fellowship) be amended by the deletion of the words "Three Guineas" and the insertion of the words "Four Guineas" in place thereof.
   (*b*) THAT article 5 (*c*) (concerning Associate Fellowship) be amended by the deletion of the words "Three Guineas" and the insertion of the words "Three Pounds Thirteen Shillings and Sixpence" in place thereof.
   (*c*) THAT article 5 (*d*) (concerning Senior Membership) be amended by the deletion of the words "Three Guineas" and the insertion of the words "Three Pounds Thirteen Shillings and Sixpence" in place thereof.
   (*d*) THAT article 5 (*e*) (concerning Membership) be amended by the deletion of the words "Two Guineas if 21 years of age or over and One Pound Eleven Shillings and Sixpence if under that age," and the insertion of "Two Pounds Twelve Shillings and Sixpence if 21 years of age or over, and Two Guineas if under that age" in place thereof.
   (*e*) THAT article 5 (*f*) (concerning discretionary powers of the Council to allow the payment of reduced fees) be amended by the deletion of the figures "£1 11s. 6d." and the insertion of the words "Two Guineas" in place thereof.
4. To elect five Members of the Council of the Society. In accordance with Article 15, the following will retire at the meeting and offer themselves for re-election:
   J. E. Allen, K. W. Gatland, S. W. Greenwood, W. R. Maxwell and A. E. Slater.

   As other additional names have been nominated and the number of nominations exceeds the number of vacancies, election will be by Postal Ballot, which will be circulated to all members beforehand.
5. General discussion of the affairs of the Society during the past year.
6. Any other business.

By Order of the Council,
L. J. CARTER,
Secretary.

A member who cannot be personally present at the meeting may appoint by proxy some other person (who must be a member of the Society) to attend and vote on his behalf subject, however, to the proviso that a proxy cannot vote except on a poll.

PRESIDENTIAL ADDRESS

Following the Annual General Meeting an address will be given by the Society's President, Dr. W. R. Maxwell on:

"SOME ASPECTS OF RECENT PROGRESS IN ASTRONAUTICS"

This will commence at approximately 7.15 p.m.

The British Interplanetary Society

LIMITED (by Guarantee)

INCOME AND EXPENDITURE ACCOUNT for the Year ended 31 December, 1960

1959 £	*Expenditure*	£ s. d.	£ s. d.
	To Office and Management Expenses—		
560	Rent, Rates, Light, Heat, Cleaning and Insurance	582 6 2	
1271	Salaries and National Insurance	1731 3 9	
883	Postage, Stationery and Telephone	1086 5 11	
262	Publicity and Advertising	268 13 9	
277	Travelling and Entertaining Expenses	264 10 11	
346	Sundry Expenses ..	350 4 7	
3599			4283 5 1
4769	„ **Publications**		5230 17 8
720	„ **Expenses of Meetings** ..		857 17 8
	„ **International Astronautical Federation—**		
1104	Contribution and Congress Expenses		677 10 11
42	„ **Income Tax**		71 16 0
	„ **Depreciation—**		
236	Furniture and Equipment	496 4 6	
50	Library	50 0 0	
286			546 4 6
500	„ **Transfer to Benevolent Fund**		– – –
	„ **Transfer to Headquarters Reserve Account**		1000 0 0
886	„ **Excess of Income over Expenditure**		118 9 7
£11,906			£12,786 1 5

1959 £	*Income*	£ s. d.	£ s. d.
	By Membership Subscriptions		
8278	**and Entrance Fees** ..		8759 16 11
361	„ **Donations**		346 13 8
	„ **Library Subscriptions and**		
2271	**Sales of Publications** ..		2774 3 3
573	„ **Advertising Receipts** ..		570 8 7
221	„ **Royalties**		68 17 0
	„ **Income from Investments—**		
35	3½% Defence Bonds ..	35 0 0	
80	Building Society Deposit Account	80 0 0	
87	Bank Deposit Interest ..	151 2 0	
202			266 2 0
£11,906			£12,786 1 5

BALANCE SHEET as at 31 December, 1960

1959 £	*Capital and Reserves*	£ s. d.	£ s. d.
	Accumulated Fund—		
4571	Balance at 1 January, 1960	5457 5 7	
886	*Add* Excess of Income over Expenditure	118 9 7	
5457			5575 15 2
—	**Headquarters Reserve Account**		1000 0 0
1914	**Compounded Subscriptions Reserve**		2078 13 6
47	**Income Tax Reserve** ..		72 1 6
7418			8726 10 2
	Current Liabilities		
506	**Subscriptions Paid in Advance**	286 16 11	
2608	**Sundry Creditors**	834 14 1	
3114			1121 11 0
£10,532			£9848 1 2

1959 £	*Fixed Assets*	£ s. d.	£ s. d.
	Furniture and Equipment—		
1680	At cost	2526 2 3	
1130	*Less* Depreciation to date	1526 2 3	
550			1000 0 0
	Library—		
530	At cost	530 4 2	
430	*Less* Depreciation to date	480 4 2	
100			50 0 0
	Investments—		
1000	3½% Defence Bonds (P.O. Issue)	1000 0 0	
2000	4% City of London Building Society Deposit Account	2000 0 0	
			3000 0 0
3650	**Total of Fixed Assets** ..		4050 0 0
	Current Assets		
305	**Sundry Debtors and Payments in Advance**	187 7 1	
	Cash at Bank—		
4532	Deposit Account ..	4532 0 0	
2026	Current Account ..	1071 12 2	
19	**Cash in Hand**	7 1 11	
6882			5798 1 2
£10,532			£9848 1 2

REPORT OF THE AUDITORS TO THE MEMBERS OF THE BRITISH INTERPLANETARY SOCIETY LTD.

We have obtained all the information and explanations which to the best of our knowledge and belief were necessary for the purposes of our audit. In our opinion proper books of account have been kept by the Society so far as appears from our examination of those books. We have examined the above Balance Sheet and annexed Income and Expenditure Account which are in agreement with the books of account. In our opinion and to the best of our information and according to the explanations given to us, the said accounts give the information required by the Companies Act, 1948, in the manner so required, and the Balance Sheet gives a true and fair view of the state of the Society's affairs as at 31 December, 1960, and the Income and Expenditure Account gives a true and fair view of the surplus of income over expenditure for the year ended on that date.

15, Craven Street, London, W.C.2.
28 *February*, 1961

K. READHEAD & CO.,
Chartered Accountants

REPORT OF COUNCIL

FOR THE YEAR ENDED 31 DECEMBER, 1960

THE Society's progress during the year 1960 was not marked by any major event of the size and importance of the International Astronautical Congress held in London during the previous calendar year, but it was nevertheless a period of considerable activity.

This report will not deal with the individual events of the year at great length, but will merely summarize them and provide other information of importance to members.

International Meetings

The most important international meeting of the year was the Eleventh International Astronautical Congress, which was held in Stockholm. This was attended by about sixty participants from Britain, most of them being members of the Society, who renewed friendships and made many new acquaintances among most congenial surroundings. The annual I.A.F. Congress has often been made the occasion of a notable astronautical feat, and in this case the first recovery of U.S. and U.S.S.R. satellites from orbit took place just before and during the Congress respectively.

Recommendations to H.M. Government on a Space Programme

The activities of the Society in bringing before the Government its views on the necessity for a space programme which were mentioned in the last Report are still continuing. In the later months of 1960, the role of the Society in this field was mainly to keep those M.P.'s who are interested in a space programme informed of the current technical position, so that they were better placed to debate the subject in the House.

The Society's advocacy, over a period of several years, of European co-operation in a space programme met with limited success towards the end of 1960, with the establishment of the permanent organization known both as E.S.R.O. (European Space Research Organization) and G.E.E.R.S. (Groupe d'Etudes Européen de Recherches Spatiales). This success could only be considered partial, however, and the Society therefore continued to express itself strongly in favour of co-operation in a technological programme which could ultimately lead to Europe becoming a third power in space.

As this report is being prepared there are indications that this programme will also be established—E.S.L.O. (European Space Launcher Organization) is the suggested name for the body to be set up to carry out the programme. Our future acitivities in this field will include support for the activities of both E.S.R.O. and E.S.L.O.—and particularly of the various British bodies which will be working in conjunction with the European groups.

Society Meetings

A feature of our activities which has become of increasing importance has been the organization of a number of symposia. These have done a great deal to enhance the Society's prestige and good attendances have been achieved, even in quite specialized subjects, for space technology is now recognized as a major technical subject, with many branches.

Some of these symposia have been held in collaboration with other societies and this is very desirable where the subject is closely connected with the work of another body. Sometimes it can also have the advantage of spreading the work of organization.

The most important of these joint symposia was that on Rocket Propulsion, held in collaboration with the College of Aeronautics and the Royal Aeronautical Society, early in January, 1961. The bulk of the work of preparing for this symposium was done during the year under review. Like all the other symposia with which we have been associated, it was well attended and the papers were of a generally high technical standard.

Other symposia held during 1960 were concerned with rocket and satellite instrumentation and with space navigation. The proceedings of the former were published in the February 1961, issue of the *Journal*; the papers on space navigation will appear in the August issue.

In addition to the symposia, the Society has continued to hold regular lecture meetings, both in London and the provinces.

Publications

The difficulty in meeting the publication scheule of *Spaceflight* which was referred to in the last Report of Council has been overcome, and it is now being issued in advance of its nominal publication date, to facilitate distribution to American readers on time. The volume of material published has been maintained (132 pages, compared with 128 in 1959), and will be increased during the coming year, as *Spaceflight* has now become bimonthly.

As in the previous year we have been encountering difficulty in achieving the publication schedule of the *Journal*, although it has continued to appear at roughly two-monthly intervals and was considerably expanded during 1960 (272 pages, compared with 192 in 1959). This increase in material published has also been maintained thus far in 1961.

Many factors are involved in the failure to regain normal publication dates which has persisted since the printing dispute of 1959. The *Journal* still contains more material than *Spaceflight*; it necessarily also includes an appreciable proportion of mathematics, which must be set into type by hand—a slow and laborious process, both during the original composition and during correction. However, we regard it as essential to maintain a high standard typographically as well as technically. Our printers co-operate with us in this respect, although a non-mathematical periodical such as *Spaceflight* is much easier and more profitable for them to handle. In this connection, we should mention that our printers are responsible for over forty different publications of varying size and frequency of issue. Any delay that might occur in one publication cannot be permitted to interfere drastically with the course of the others, particularly where these are issued at frequent intervals. The periodicals handled by our printers include five monthlies, and we shall be in a much stronger bargaining position *vis-à-vis* the printer when we can afford to issue monthly publications and can provide the staff to handle this volume of material.

These points are not intended as excuses for the *Journal* remaining behind schedule but more as a partial explanation. The regular and punctual appearance of our publications is an important factor for the health of the Society and the development of astronautics in Britain, and a special effort will be made by Editor and printers to remedy the situation during the coming months.

Financial Status and Membership

While the financial state of the Society has not improved to the extent which the Council and Officers would have liked, we were nevertheless able to show a profit on the year's activities. As you will see from the published Annual Accounts, this has enabled a Headquarters Fund to be started with a transfer of £1000 from the Society's revenue.

However, the need for increasing our income is greater than ever, as we need more permanent staff, larger premises and more frequent publications. It does not seem as though this increase in income can be achieved by an increase in membership alone, for despite the considerable efforts of the Membership Committee the rate of growth of the Society has not increased to any marked extent, and other means of acquiring funds must be sought.

A feature of the recent growth of the Society has been the increased ratio of Fellowship and Associate Fellowship grades to Senior Membership and Membership grades. This is probably accounted for by the fact that the layman who is interested in space research can now find much of what he wants in popular technical magazines and the daily press, whereas the professional man and industrialist are becoming more and more aware of the benefits which the Society has to offer.

In saying this, it must also be emphasized that while the Society is expanding its activities in the professional field, there is no intention of neglecting the needs of Members, and Council is planning the introduction of increased services of especial interest to them as and when finances and staff permit.

Lecture Halls

It has been apparent for some time that the Society would benefit from holding its London lectures in places associated with the world of learning and equipped with modern lecture facilities. Early in 1960 it was decided that all lectures arranged in future should be held in the hall of a convenient learned society or other organization of comparable status.

The new Lecture Hall of the Royal Aeronautical Society was opened in December, 1960, and the British Interplanetary Society was invited to hire it as required and when available. This offer was accepted and the Hall has since been used on several occasions with very satisfactory results.

Many of the Society's future meetings will be held at this venue, but it will not be employed exclusively. Thus, the 1961 session includes meetings in the Halls of the Federation of British Industry and the American Embassy.

Formation of New Branches

Three new provisional groups were formed during the period under review: in New South Wales, South Australia and Victoria. We hope that they will flourish.

Staff

Mr. L. J. Carter, who for many years has been employed as Secretary on a part-time basis, took office as our first full-time salaried Secretary in July, 1960, and thus served as such for only 6 months in the period under review. The full benefit of his appointment will only be felt in 1961. Mr. Carter is aided by one full-time clerical assistant and various part-time employees, but it is planned to appoint a second full-time girl to the staff during the current year.

Even when that is done, our headquarters will be understaffed for the work which it has to undertake, but the income of the Society must be increased before we can afford the staff we really need. In the meantime, members are asked to restrict their correspondence with headquarters to essentials. The reply to a quite trivial enquiry can cost two or three shillings in labour, and delay more important tasks.

Council, Committees and Officers

In the autumn of 1960, Dr. Shepherd completed his term of office as leader of the Society; the word *leader* is used here because just before Dr. Shepherd's term ended the Council decided that the Society should have a President instead of a Chairman of Council, so that in the last year Dr. Shepherd served under both titles.

Dr. Shepherd completed the maximum period of office allowed by the Articles (3 years) and this period was probably the most eventful in the Society's history. During it we witnessed the launching of the first artificial satellites and it also involved the organization of the first really large International Astronautical Congress to be held in this country. Dr. Shepherd had held office as Chairman of Council for a previous 3-year period and all members will wish to join in thanking him for all the hard work he has put in. It is indisputable that nobody has done more good for the Society in recent years.

In addition to the departure from the Council of Mr. D. J. Cashmore (referred to in the last Report of Council) we also lost Mr. E. T. B. Smith, who is now with the British Joint Services Mission in Washington, D.C. At the last Annual General Meeting their places on the Council were filled by Dr. W. F. Hilton and Mr. G. K. C. Pardoe, two well-known figures in the aerospace industry.

In closing, I must thank my fellow-councillors for the effort they have made during the past year. As always, particular thanks are due to our two Honorary Editors, Mr. K. W. Gatland and Mr. G. V. E. Thompson, for their continued work in bringing out our publications—work which takes up many hours of their spare time. Similar mention must be made of the work of Mr. J. Humphries and his team of abstractors (listed in full on p. 122) who are responsible for the ASTRONAUTICAL ABSTRACTS section of the *Journal*.

W. R. MAXWELL,
President.

MEMBERSHIP

The number of members in the various grades at 31 December, 1959 and 1960, were as follows:

	1959	1960
Honorary Fellows	5	5
Fellows	1194	1256
Associate Fellows	35	149
Senior Members	162	197
Members	1907	1685
	3303	3292
Corporate Members	2	3

COUNCIL AND OFFICERS

President

W. R. MAXWELL, B.Sc., Ph.D.

Past-President

L. R. SHEPHERD, B.Sc., Ph.D.

Vice-Presidents

M. BRENNAN, B.Sc., M.I.Mech.E., F.R.Ae.S.
K. W. GATLAND, F.R.A.S.

Ordinary Members of Council

J. E. ALLEN, B.Sc.(Eng.), A.M.I.Mech.E., A.F.R.Ae.S., A.F.I.A.S.
A. H. S. CANDLIN, B.Sc. (Tech. Chem.), Assoc. I. Mech.E.

M. N. GOLOVINE, M.B.E., A.C.G.I., A.F.R.Ae.S.
S. W. GREENWOOD, B.Sc., M.Eng., A.M.I.Mech.E., A.F.R.Ae.S.
W. F. HILTON, Ph.D., D.Sc., A.R.C.S., D.I.C., F.R.Ae.S.
D. HURDEN, B.A., G.I.Mech.E.
N. H. LANGTON, M.Sc., Ph.D., A.M.Brit.I.R.E., A.Inst.P.
N. R. NICOLL
G. K. C. PARDOE, B.Sc.(Eng.), D.L.C., A.F.R.Ae.S.
A. E. SLATER, M.A., M.R.C.S., L.R.C.P., F.R.Met.S.
G. V. E. THOMPSON, B.Sc., B.Sc.(Eng.), A.R.C.S., F.R.I.C., A.I.L., L.I.M.

Secretary
L. J. CARTER, A.C.I.S.

COMMITTEES

The main committees of the Society which have served during the year were constituted as follows at 31 December, 1960:

FINANCE AND GENERAL PURPOSES COMMITTEE

*SHEPHERD, Dr. L. R. (*Chairman*) — *GATLAND, Mr. K. W.
*CARTER, Mr. L. J. — THOMPSON, Mr. G. V. E.

* Benevolent Fund Trustees

HONOURS AND AWARDS COMMITTEE

SHEPHERD, Dr. L. R. (*Chairman*) — BRENNAN, Mr. M.
ALLEN, Mr. J. E. — CARTER, Mr. L. J.

I.A.F. COMMITTEE

SHEPHERD, Dr. L. R. (*Chairman*) — MAXWELL, Dr. W. R.
CANDLIN, Mr. A. H. S. — THOMPSON, Mr. G. V. E.
CARTER, Mr. L. J.

MEMBERSHIP COMMITTEE

BRENNAN, Mr. M. (*Chairman*) — HURDEN, Mr. D.
CANDLIN, Mr. A. H. S. — PARDOE, Mr. G. K. C.

PROGRAMME COMMITTEE

GATLAND, Mr. K. W. (*Chairman*). — HURDEN, Mr. D.
CARTON, Mr. D. S. — LANGTON, Dr. N. H.
FEA, Mr. K. H. — NICOLL, Mr. N. R.

PUBLICATIONS COMMITTEE

THOMPSON, Mr. G. V. E. (*Editor* and *Chairman*) — LANGTON, Dr. N. H.
CANDLIN, Mr. A. H. S. (*Assistant Editor*) — SLATER, Dr. A. E.

SPACEFLIGHT ADVISORY BOARD

GATLAND, Mr. K. W. (*Editor* and *Chairman*) — CROSS, Mr. C. A.
ALLWARD, Mr. M. F. — HURDEN, Mr. D.
SLATER, Dr. A. E.

TECHNICAL POLICY COMMITTEE

MAXWELL, Dr. W. R. (*Chairman*) — LANGTON, Dr. N. H.
ALLEN, Mr. J. E. — PARDOE, Mr. G. K. C.
BRENNAN, Mr. M. — SHEPHERD, Dr. L. R.
HILTON, Dr. W. F. — THOMPSON, Mr. G. V. E.

EUROPEAN SPACEFLIGHT SYMPOSIUM COMMITTEE

SHEPHERD, Dr. L. R. (*Chairman*) — GOLOVINE, Mr. M. N.
CANDLIN, Mr. A. H. S. — THOMPSON, Mr. G. V. E.
CARTER, Mr. L. J.

THE BRITISH INTERPLANETARY SOCIETY BENEVOLENT FUND

Report of the Trustees for the Year ended 31 December, 1960

	£ s. d.	£ s. d.
Balance at 1.1.1960 brought forward	910 11 1	
Donations received from members in response to our appeal	277 15 5	
Deposit Account Interest Received	13 6 9	
	1201 13 3	
Less Disbursements:—		
Wreaths — 3 18 0		
Legal fees for preparation of Trust Deeds — 16 0 0		
Cost of Appeal Letters — 38 18 0		
	58 16 0	
Balance at 31.12.1960 carried forward	£1142 17 3	

Investment Holdings at 31.12.1960.

	£ s. d.
Cash Deposit with City of London Building Society	500 0 0
Cash at Bank: Deposit Account	400 0 0
Cash at Bank: Current Account	242 17 3
	£1142 17 3

Certified to be a true audited copy:

L. J. CARTER, K. W. GATLAND, L. R. SHEPHERD — *Trustees appointed by the Council.*

NEWS AND ANNOUNCEMENTS

B.I.S. NEWS

Future Symposia

The lecture programme for the second half-session will include two one-day symposia, each to consist of between six and eight papers, with discussion. Some of the papers to be presented will be by recognized authorities in the subjects concerned who have been specially invited to participate in the proceedings, but other contributions will be welcomed. Authors who wish to present papers at either symposium are asked to send a synopsis to the Secretary.

On Wednesday, 22 **November**, there will be a symposium on Materials in Aerospace Technology. This is intended to approach the subject from the viewpoint of the materials engineer, metallurgist, etc., rather than that of the rocket designer, although it will naturally be of great interest to the latter: the emphasis is on the need to develop improved materials and how this can be done. It is hoped that the papers and discussion will cover such topics as behaviour of re-entry materials, refractories for rocket nozzles, ultra-light alloys, ion rocket materials, effect of solar and cosmic radiation on structural and electronic materials, advanced fabrication techniques, semiconductors in aerospace technology, plastics for space applications, etc.

The other symposium, to be held in mid-December, will be concerned with auxiliary power supplies for spacecraft and space equipment. Relevant topics will thus include batteries and solar cells for satellites and space probes, effect of the extra-terrestrial environment (radiation, meteorites, vacuum, temperature, etc.) on their operation, fuel cells, nuclear power sources, auxiliary power requirements for aerospace equipment, use of solid propellents for emergency power in space, etc.

Several other symposia are also being planned for 1962 and later years. Details will be announced later, but again members and others who contemplate presenting papers are requested to write to the Secretary. The symposia likely to be held early in 1962 will deal with rocket propulsion, devices for planetary investigation, and space medicine.

Western Branch Secretary

Mr. P. J. Ladd (Ashleigh, Cockhill, Trowbridge, Wiltshire) has replaced Mr. R. Sykes as Secretary of the Western Branch.

JOINT ACTIVITIES

Twelfth International Astronautical Congress

The Twelfth International Astronautical Congress will be held in Washington, D.C., during the week **1-7 October, 1961**, and is being organized by the American Rocket Society. The address of the Congress Secretariat is c/o American Rocket Society, 500 Fifth Avenue, New York 36, N.Y., U.S.A.

The Provisional Congress Programme is given below. All of the technical sessions and the banquet will be held at the Marriott Twin Bridges Hotel, Highway U.S.1, Washington 1, D.C. This is the world's largest motor hotel; rooms have been reserved for Congress participants who also wish to stay at the hotel, and there are special rates for European guests.

Participation is open to all and the fee for active participation will be $25 per person (approximately £9); this does not cover the provision of preprints—at this Congress only abstracts will be officially available. Registration for wives for the ladies programme is free; tickets for the Banquet cost $10 per person.

A limited supply of registration forms for the Congress are available from the Secretary, B.I.S., 12, Bessborough Gardens, London, S.W.7, but overseas members will find it easiest to write direct to the American Rocket Society.

PROVISIONAL CONGRESS PROGRAMME

Sunday, 1 October

All day	Registration.
Evening	Mixer.

Monday, 2 October

Morning	I.A.F. Plenary Session.
Afternoon	I.A.F. Plenary Session.
Evening	I.A.F. Opening Ceremony. Informal Reception.

Tuesday, 3 October

Morning	Astrodynamics and Guidance Roundtable. Space Propulsion Session. Academy of Astronautics Meeting.
Afternoon	Structures Roundtable. Energy Conversion Session.
Evening	Formal Reception.

Wednesday, 4 October

Morning	Space Physics Roundtable. Combustion Session. Institute of Space Law.
Afternoon	Space Medicine Roundtable. Astrodynamics and Guidance Session. Institute of Space Law.
Evening	Special Evening Programme.

Thursday, 5 October

All day	Boat tour to Mount Vernon.
Evening	The Congress Banquet.

Friday, 6 October

Morning	I.A.F. Plenary Session. Space Communications Roundtable. Vehicles Session.
Afternoon	Instrumentation Roundtable. Bioastronautics Session. Space Physics Session.

Saturday, 7 October

Sightseeing and trips to plants in Washington area.

Second Rocket Propulsion Symposium

The Second Rocket Propulsion Symposium is being organized jointly by the British Interplanetary Society, the College of Aeronautics, and the Royal Aeronautical Society. It will follow the same pattern as the First Symposium held in January, 1961, and have as its main aim the encouragement, through formal and informal discussion, of the dissemination of unclassified ideas on all aspects of rocket propulsion, with particular emphasis on British work in this field. For the Second Symposium, the main theme will be Rocket Combustion Chamber Processes.

The meeting will be held at the College of Aeronautics, Cranfield, Bletchley, Buckinghamshire. It will commence on Wednesday, **25 April, 1962**. Notice of intention to present a paper, with proposed title and synopsis, should be given by 15 October, 1961. Further information is available from the Secretary, British Interplanetary Society, 12 Bessborough Gardens, London, S.W.1.

ASTRONAUTICAL ABSTRACTS

Edited by J. HUMPHRIES

1961-62 PART 3

Abstracting panel:

C. FLEISHER, J. FOLEY, J. S. GRIFFITH — HAWKER SIDDELEY AVIATION LTD.; ADVANCED PROJECTS GROUP — C. E. S. HORSFORD, J. HUMPHRIES, A. E. SLATER — G. V. E. THOMPSON, E. WHITE

A complete list of journals abstracted together with abbreviations used is to be included in the 1959-60 index.

The following abstracts refer to books noted in this issue: 804, 805, 807-12, 857, 915-20, 943, 971, 973.

1—ASTRONOMY

.5 *Planets (except Earth)*

[*See also* abstract no. 804]

(750) **The emission spectrum of the night side of Venus.** B. Warner. *Month. Not. Roy. Astronom. Soc.*, **121** (3), 279–83 (1960). Statistical analysis of Kozyrev's observed Venus spectrum reveals presence of nitrogen and probably oxygen I, II.

(751) **Mapping the planets.** Z. Kopal. *New Scientist*, **8**, 1511–3 (8 *Dec.*, 1960). Includes map of Mars. Popular.

.7 *Moon*

(752) **Impact of rocket *Lunik II* on the Moon.** M. Vocel. *Bull. Astronom. Insts. Czech.*, **11** (3), 206–13 (1960). Phenomena produced by impact of rocket are examined and discrepancy between theory and observation pointed out.

.8 *Meteors*

(753) **Meteoric abrasion studies proposed for Vanguard.** M. J. Swetnik. *University of Maryland, Physics Department, Tech. Report* 63 (1956).

(754) **Are metallic meteorites a key to the reentry problem?** R. E. Maringer and G. K. Manning. *Iron Age*, **183**, 93–6 (9 *April*, 1959).

2—PHYSICS

.1 *General*

(755) **Relativity and space travel.** J. R. Pierce. *Inst. Radio Engrs. Proc.*, **47**, 1053–61 (*June*, 1959). For discussion on this paper see *Inst. Radio Engrs. Proc.*, **47**, 1778–80 (*Oct.*, 1959).

(756) **Antiparticles in space.** E. W. Hones. *Phys. Rev. Letters*, **2**, 509–10 (15 *June*, 1959). (8 *refs.*)

.5 *Heat and Thermodynamics*

[*See also* abstracts nos. 871 and 876]

(757) **A method of determining the transient temperature distribution in an entry-vehicle heat sink.** J. C. Tearnen. *Amer. Soc. Mech. Engrs. Prepr.* 59–*AV*–31, 4 pp. (1959). (2 *refs.*)

(758) **Estimation of heat transmission in the turbulent region during re-entry through the atmosphere.** M. Tucker and D. Eberly. *Paper V–5, Second International Congress of Rockets and Satellites, Paris* (1959). (*In French.*)

(759) **Considerations in the application of evaporative cooling systems to hypersonic vehicles.** E. Kaplan. *Society of Automotive Engineers, Paper* 547, *National Aeronautic Meeting* (31 *March*–3 *April*, 1959).

(760) **Similarity parameters for surface melting of a blunt nosed body in a high velocity gas stream.** L. Lees. *ARS J.*, **29**, 345–54 (*May*, 1959). (20 *refs.*)

(761) **Heat received by a missile in the course of re-entry.** E. Brun. *Seminar in Astronautics and Space Sciences, Univ. of Rome* (18–29 *May*, 1959). (*In French.*)

(762) **Particular study of the heat received by the nose of a missile.** E. Brun. *Seminar in Astronautics and Space Sciences, Univ. of Rome* (18–29 *May*, 1959). (*In French.*)

(763) **Evaporative film cooling of blunt bodies in hypersonic flow and its application to re-entry vehicles.** R. Hermann. 11*th Internat. Astronaut. Congr.*, 12 pp. (1960). Evaporative film cooling on blunt-nosed bodies was studied in a 12 in. × 12 in. wind tunnel at Mach No. 7 with stagnation temperatures up to 2500° R. (1370° K.). Water as coolant was supplied continuously through orifices near the stagnation point of a hemisphere-cylindrical body and a blunt cone (10° half-angle) to form an evaporating film covering the body. Ice formation developed. Thermodynamic and similarity analyses of the system are given, and the application of the method and its advantages for cooling re-entering satellite vehicles are discussed. (9 *refs.*)

.8 *Other Upper Atmosphere Phenomena*

(764) **To the frontiers of the atmosphere.** P. de Latil. *Sciences et Avenir*, **131** (*Jan.*, 1958). (*In French.*)

(765) **Absorption and electron distribution in the F_2 layer determined from measurements of transmitted radio signals from Earth satellites.** A. N. Kazantsev. *Planetary and Space Sci.*, **1**, 130–5 (*April*, 1959).

(766) **Artificial sodium clouds. Wind speed, turbulence and density of the upper atmosphere.** J.-E. Blamont. *C.R. Acad. Sci., Paris*, **249**, 1248–50 (5 *Oct.*, 1959). (*In French.*) (2 *refs.*)

(767) **Results of scientific investigations made by Soviet sputniks and cosmic rockets.** V. I. Krassovskii. *Astronautica Acta*, **6** (1), 32–47 (1960). Hitherto unpublished information is given on measurements in the upper atmosphere and in cosmic space.

(768) **Recent experiments from rockets and satellites.** H. Friedman. *Astronom. J.*, **65**, 264–71 (*June*, 1960). Ultraviolet emission of night sky and spectroheliograms in Lyman alpha taken by means of rockets.

(769) **Preliminary evaluations of day airglow rocket measurements of 6300Å.** H. A. Cohen, R. E. Grojean and A. D. Bailey. *Optical Soc. Amer. Paper WB*16, (*Oct.*, 1960). Airglow data obtained (6300–6040 Å.) at 60–240 km. with a rocket-borne scanning spectrometer flown at White Sands on 21 Aug., 1959. Strength of the 6300 Å. line well below that predicted.

(770) **Some discoveries from satellite orbits.** D. G. King-Hele. *New Scientist*, **8**, 1193–6 (3 *Nov.*, 1960). Atmospheric data from changes in orbits. Solar disturbances affect density above 200 km. Popular account.

3—CHEMISTRY AND MATERIALS

.1 *General*

(771) **Compatibility of materials with liquid oxygen**. H. M. Peckham and R. L. Hauser. *Proc. 4th Cryogenic Engng. Conf., Cambridge, Mass., U.S.A.*, 26–46 (1958).

.2 *Chemistry*

[*See also* abstract no. 892]

(772) **Hydrogen derivatives of boron**. J. Cueilleron. *Tech. Sci. Aeronaut.*, 279–83 (*Dec.*, 1958). (*In French.*) Pentaborane and decaborane have calorific values 70% higher than petrol; the discovery of B and its H compounds, their preparation, structure and their chemical and physical properties are discussed.

.3 *Metallurgy*

(773) **Metals for interplanetary flight**. F. L. LaQue. *Steel Processing*, **12**, 691–4, 709–10 (*Dec.*, 1957).

(774) **Selection and evaluation of rare or unusual metals for application to advanced weapons systems. I. A literature survey**. B. Love. *U.S. Air Force, Wright Air Force Devel. Center Tech. Rept.* 57–666, 174 pp. (*June*, 1958).

(775) **Feasibility of titanium for welded missiles**. C. E. Hartbower, G. M. Orner and D. M. Daley, Jnr. *Welding J.* (*Welding Res. Suppt.*), **38** (9), 345-s—353-s (*Sept.*, 1959). Evaluation based on short-time elevated-temp. tensile properties and a notch-tensile-impact test, alloys studied being Ti–4Al–2V–1Mo–1Cr–1Sn, Ti–6Al–4V and Ti–5Al–2.5Sn. Most welds were made by the inert-gas-shielded, tungsten-arc process, using Ti–6Al–4V filler wire. Tensile properties were satisfactory although there was some loss of ductility; notch sensitivity was a problem.

(776) **What space craft builders want from metals in years ahead**. *Iron Age*, **184**, 115–17 (24 *Sept.*, 1959). Based on Annual Forecast Report of the Aerospace Industries Assn.

(777) **Deep-drawing high-strength cases for missile motors**. R. S. Townend. *Machinery*, **66**, 111–14 (*Nov.*, 1959).

.5 *Plastics*

(778) **Will heat-resistant plastics replace steel?** H. Raech. *Amer. Machinist*, **103**, 110–12 (7 *Sept.*, 1959).

4—BIOLOGY AND MEDICINE

.1 *General*

(779) **Occurrence of life in the universe**. S. S. Huang. *Amer. Scientist*, **47**, 397–402 (*Sept.*, 1959).

(780) **Biological control of enclosed environments**. C. G. Golueke. *Sewage and Industr. Wastes*, **31**, 1125–42 (*Oct.*, 1959).

(781) **Biological contamination of the Moon**. C. Sagan. *Proc. Nat. Acad. Sci., U.S.A.*, **46** (4): 396–402 (*April*, 1960). Four possible circumstances which could lead to undesirable contamination are discussed.

.2 *Botany*

(782) **Selection of an Alga for a photosynthetic gas exchanger**. R. J. Benoit, F. Trainor and A. Bialecki. *Wright Air Development Division Tech. Rept. No.* 60–163, *Wright Patterson Air Force Base, Ohio* (*Feb.*, 1960). A detailed survey of the plant kingdom reveals that a thermophilic strain of the Alga *Chlorella* seems to have the best combination of desirable characteristics for a closed cycle system.

.4 *Anatomy and Physiology*

(783) **Survival in space tested thanks to tele-physiology**. P. de Latil. *Sciences et Avenir*, **130**, 638–642, 651 (*Dec.*, 1957). (*In French.*)

(784) **Space medicine**. P. de Latil. *Sciences et Avenir*, **131** (*Jan.*, 1958). (*In French.*)

(785) **Human tolerance to prolonged forward and backward acceleration**. N. P. Clarke and S. Bondurant. *Aero Medical Lab., Wright Air Development Center, U.S.A.F. report*, 34 pp. $1.00 (1959).

(786) **Environmental testing of future spacemen**. M. Traite, W. Welkowitz, J. Kilduff and C. Purpuro. *Electronics*, **32** (42), 65–9 (16 *Oct.*, 1959). (4 *refs.*)

(787) **A restraint system enabling pilot control under moderately high acceleration in a varied acceleration field**. H. A. Smedal, G. W. Stinnett and R. C. Innis. *N.A.S.A. Tech. Note No. D–91* (*May*, 1960). Experiments with a centrifuge employing accelerations up to 7 *g* from various directions for 2 to 5 min. duration, such as would be expected in a re-entry vehicle employing lift. Resulting from the experiments, a suitable restraint system was evolved.

(788) **Putting man in space on display**. K. Anderson. *Control Engng.*, **7** (6), 29–30 (*June*, 1960).

(789) **Perception of the horizontal and vertical in simulated subgravity conditions**. G. J. D. Schock. *Armed Forces Med. J.*, **11** (7), 786–93 (*July*, 1960). During immersion in water, perception of the horizontal and vertical is impaired when the head is tilted from the vertical, whether the body also is tilted or not.

(790) **Perception of linear motion following unilateral labyrinthectomy: variation of threshold according to the orientation of the head**. E. D. Walsh. *J. Physiol.*, **153** (2), 350–7 (*Sept.*, 1960). Experiments suggest that the otolith organs (left and right saccules and utricles) are sensitive only to those linear accelerations (including gravity) which produce shearing forces in the macula, and not to accelerations perpendicular to the plane of the macula. Also the sensitivity is greater when the saccular otolith particles hang than when they press on the macula. (10 *refs.*)

(791) **Aerospace nuclear safety**. J. A. Connor. *Aerospace Med.*, **31**, 797–806 (*Oct.*, 1960). A general review of relevant problems. (20 *refs.*)

(792) **Tissue ionization dosages in proton radiation fields in space**. H. J. Schaefer. *Aerospace Med.*, **31**, 807–16 (*Oct.*, 1960). Types of radiation damage by protons from cosmic radiation, the inner Van Allen belt and solar flares are compared, and are shown to be so different, especially in regard to relative damage to the skin and to deeper tissues, that accepted classifications of penetrating powers are inadequate and need revision (9 *refs.*)

(793) **The biology of space travel**. *Brit. Med. J.*, 1960, **2** (5205), 1079–80 (8 *Oct.*, 1960). Report of a Symposium on "The Biology of Space Travel," held by the Institute of Biology in London, 29–30 Sept., 1960.

(794) **Observations on human subjects living in a "slow rotation room" for periods of two days: Canal sickness**. A. Graybiel, B. Clark and J. J. Zariello. *Naval School of Aviation Medicine, Pensacola, Fla., Research Project No. MR005* (15 *Oct.*, 1959). Five subjects were rotated at rates from 1·71 to 10·0 rev./min. for prolonged periods. Procedure is recommended for selecting personnel for orbiting satellites.

(795) **Studies of primate tolerance to some complex accelerations**. N. P. Clarke and R. N. Headley. *Wright Air Development Center Tech. Rept. No.* 59–630, *Wright-Patterson Air Force Base, Ohio* (*Nov.*, 1959). Five primates were exposed to accelerations of the type expected with unstable re-entry of satellite vehicles (including oscillations). All animals could make co-ordinated movements almost immediately afterwards.

(796) **Human tolerance to whole body sinusoidal vibration**. E. B. Magid, R. R. Coermann and G. H. Ziegenruecker. *Aerospace Med.*, **31** (11), 915–24 (*Nov.*, 1960). Tolerances of 15 subjects to 16 different forms of pain and discomfort were found during 1- and 3-min. runs at vibration rates from 1 to 15 cycles/sec (2 *refs.*)

(797) **Ability of pilots to perform a control task in various sustained acceleration fields**. H. A. Smedal, B. Y. Creer and R. C. Wingrove. *Aerospace Med.*, **31** (11), 901–6 (*Nov.*, 1960). Accelerations imposed were those expected in a re-entry lifting vehicle with the pilot facing forward. A suitable restraint system was devised. (10 *refs.*)

(798) **Talk with an astronaut**. K. Owen. *Flight*, **78**, 841–4 (25 *Nov.*, 1960). Training of Project Mercury astronauts.

.7 *Psychology*

(799) **Environmental requirements of sealed cabins for space and orbital flights: A second study. Part 3: Effects of long term confinement on personality and perception**. N. M. Burns and R. B. Ziegler. *Naval Air Materiel Center, Air Crew Equipment Lab., Philadelphia, Pa., Report No. NAMC–ACEL–415* (22 *July*, 1960). Results of confining six men for 8 days in a simulated space vehicle. Also a survey of the relevant literature.

5—AVIATION AND AERODYNAMICS

.2 *Aerodynamics*

(800) **Aerodynamics for space flight**. E. P. Williams and C. Gazley. *Rand Corp. Rept. P*–1256, 26 pp. (24 *Feb.*, 1958).
(801) **Drag brake proposed for M–I–S**. *Missiles and Rockets*, **5** (26), 18–21 (22 *June*, 1959). Avco proposal.
(802) **An experimental investigation of the effect of ejecting a coolant gas at the nose of a blunt body**. C. H. E. Warren. *J. Fluid Mech.*, **8**, 400–17 (*July*, 1960). Nitrogen and helium coolant gases have been ejected "straight out" or with "swirl" from the nose of a bluff body at a nominal Mach number of 5·8. Providing that the external flow is not disturbed the "straight out" ejection is found to reduce the temperature of the model surface. (7 *refs.*)

.3 *Rocket-propelled Aircraft*

(803) **Hypersonic rocket planes; Concerning the design of hypersonic rocket planes (and) Problems which will have to be solved.** MCL–385/V, order from SLA Translations Center, John Crerar Library, 86 East Randolph St., Chicago 1, Ill., U.S.A. or Photoduplication Service, Publications Board Project, Library of Congress, Washington, D.C., U.S.A., microfilm $2.40, photostat $3.30. [Translated from *Sovetskaya Aviatsiya*, 1959, (189), 4 (1959).] U.S. plans for constructing rocket planes capable of exceeding the speed of sound by 5, 10 or 15 times and at altitudes of 80 to 100 km. over distances ranging from 35,000 km. to several times round the Earth; problems involved.

6—ASTRONAUTICS

.1 *General*

[*See also* abstract no. 922]

(804) **Introduction to space**. L. A. Dubridge. 20s. *Oxford Univ. Press. Columbia Univ. Press*, U.S.A. Four lectures to laymen: (1) Problems of attaining orbital flight, (2) Discovery of Van Allen belts, (3) Nearer planets, (4) Universe.
(805) **Design of language for cosmic intercourse**. H. Frendenthal. *North Holland Pub. Co.*, 224 pp., 45s. An attempt to construct a syntax, semantically related to a conceptual system founded on mathematics.
(806) **From "Sputnik" to the Moon**. G. Lacoste. *Sciences et Avenir*, **131** (*Jan.*, 1958). (*In French.*)
(807) **Seeing the Earth from space**. I. Adler. $3.50, *Day, N.Y.* (1959). Juvenile. U.K. edition being published by Dobson Books.
(808) **First into outer space**. T. J. Gordon and J. Scheer. $3.95, *St. Martins Press, N.Y.* (1959).
(809) **Target for tomorrow**. I. M. Levitt. $4.95, 328 pp. *Fleet Pub. Co., New York* (1959). Popular.
(810) **Space weapons**. J. F. Loosbrock (ed.). 245 pp. *F. A. Praeger, Inc., New York* (1959).
(811) **New dimensions of flight**. L. Zarem. $4.50. *Dutton, N.Y.* $4.75, *Smithers and Bonellie, Toronto* (1959).
(812) **Time in space**. E. Lewellyn-Thomas. *Proc. Canad. Astronaut. Soc.*, **1** (1), 39–42 (*Feb.*, 1959).
(813) **Convair astronautics plant; newest of the space vehicle industry**. C. O. Herb. *Machinery*, **65**, 136–43 (*July*, 1959).
(814) **Commonwealth spaceflight symposium**. G. V. E. Thompson. *Aircraft Engng.*, **31** (10), 315 (*Oct.*, 1959). Summaries of papers given at the symposium held at Church House, Westminster, London, August, 27–29, 1959.
(815) **Britain and space technology**. *Aeroplane*, **99**, 720 (25 *Nov.*, 1960).
(816) **Mount Kenya launch site proposal**. E. G. D. Andrews. *Flight*, **78**, 836 (25 *Nov.*, 1960).

.2 *Artificial Satellites*

[*See also* abstracts nos. 753, 765, 767, 768, 780, 839, 843-5, 850-56, 879, 916, 920, 963, 966 and 969]

(817) **Soviet satellites and rocket developments**. W. Michely. *Luftfahrttechnik*, **4**, 38–44 (*Feb.*, 1958). (*In German.*)
(818) **Manned aircraft to manned satellites**. K. E. van Every. *Soc. Automot. Engrs. J.*, **66**, 64–7 (*July*, 1958).
(819) **Radiation observations with satellite 1958ε**. J. A. Van Allen, C. E. McIlwain and G. H. Ludwig. *J. Geophys. Res.*, **64**, 271–86 (*March*, 1959).
(820) **Soviet Earth satellites**. O. K. Sapounov. *Inst. Petroleum Rev.*, **13**, 141–6 (*May*, 1959).
(821) **Environmental control key to success of the manned Earth satellite: engineering data file**. H. H. Christman. *Heating—Piping*, **31**, 151–66 (*Oct.*, 1959). (*refs.*)
(822) **Long distance communication**. R. J. Hitchcock. *Wireless World*, **66**, 161–3 (*April*, 1960). Popular review of present techniques and the possible use of Earth satellites. (2 *refs.*)
(823) **Magnetic field effects on artificial satellites**. R. H. Wilson. *Sky and Telescope*, **20** (2), 77 (*Aug.*, 1960). Effects of magnetic fields upon rates of rotation of satellites are discussed with possible application to evolution of solar system.
(824) **Simulating radiation in orbit**. *Environmental Quart.*, **6**, 32–33 (*Oct.*, 1960). Popular description of Lockheed Missiles and Space Division's orbital simulator. Vacua down to 10^{-6} mm. Hg and temperatures from −320° F. to +500° F. (—195 to + 260°C.) can be programmed. Infra-red radiation can be applied directionally.
(825) **TIROS I: Sensor instrumentation and operation**. S. Sternberg. *Optical Society of America Paper WA1*. (*Oct.*, 1960). Emphasizes major sensor subsystem: infra-red horizon scanners, sun sensors and vidicon cameras. Design and operation of the equipment.
(826) **A proposal for a British communication satellite**. W. F. Hilton. *New Scientist*, **8**, 907–9 (6 *Oct.*, 1960). Six-satellite scheme proposed.
(827) **Streetcar satellite (first Anglo-American spacecraft to be prototype all purpose vehicle)**. *Flight*, **78**, 631 (21 *Oct.*, 1960).
(828) **Lunar satellite**. *Aeroplane*, **99**, 638–9 (11 *Nov.*, 1960).
(829) **A new weather satellite**. *Aeroplane*, **99**, 743 (2 *Dec.*, 1960).
(830) **Mercury and after**. K. Owen. *Flight*, **78**, 867–9 (2 *Dec.*, 1960). Organisation and programming of Projects Mercury and Apollo.
(831) **Recoverable satellite projects**. *Aeroplane*, **99**, 761 (9 *Dec.*, 1960).

.3 *Lunar and Planetary Probes*

[*See also* abstracts nos. 751, 841, 846 and 849]

(832) **For a trip to the moon. . . .** C. R. Lewis. *Soc. Automot. Engrs. J.*, **66** (1), 85 (*July*, 1958).
(833) **Minimum propulsion for soft Moon landing of instruments**. D. S. Carton. *College of Aeronautics Note* 94 (*July*, 1959). [*See also* abs. no. 1222, *J.B.I.S.*, **17**, 186 (1959–1960).]

.4 *Spaceships*

(834) **The principle of an anti-gyratory device**. M. Lunc. *Bull. Acad. Polon. Sci.*, **7**, 69–72 (1959). (*In French.*)
(835) **Vibration and noise problems expected in manned space craft**. H. E. Von Gierke. *Noise Control*, **5**, 8–16 (*May*, 1959).
(836) **New outer space cabin lab to supply valuable data**. L. N. Becklund. *Heating—Piping*, **31**, 110–13 (*Sept.*, 1959).
(837) **What's ahead in fluid power for space craft**. F. Mladinish, E. T. Raymond and W. F. Talbot. *Appl. Hydr. Pneum.*, **12**, 81–6 (*Sept.*, 1959).
(838) **Towards a recoverable space booster**. *Aeroplane*, **99**, 719 (25 *Nov.*, 1960).

.6 *Orbits*

[*See also* abstract no. 943]

(839) **Observations of the Russian satellites and the structure of the outer terrestrial atmosphere**. H. K. Paetzold. *Planetary and Space Sci.*, **1**, 115–24 (*April*, 1959).

(840) **Study of the oscillatory motion of manned vehicles entering the Earth's atmosphere.** S. C. Sommer and M. Tobak. *N.A.S.A. Memo.* 3-2-59*A*. 30 pp. (*April*, 1959).

(841) **Determining lunar mission guidance requirements.** B. M. Rosen. *Sperry Engng. Rev.*, **12** (2), 27–33 (*June*, 1959).

(842) **Guidance systems in manned space flight.** S. T. Cap and N. P. White. *Electronics*, **32** (33), 49–51 (14 *Aug.*, 1959). System for X-15.

(843) **Determination of the orbit of an artificial satellite.** J. T. Anderson. *Inst. Radio Engrs. Proc.*, **47**, 1658–9 (*Sept.*, 1959).

(844) **Concerning the mechanics of artificial satellites of the Earth.** M. Roy. *C.R. Acad. Sci., Paris*, **249**, 1424–5 (19 *Oct.*, 1959). (*In French*).

(845) **Lunar-solar perturbations of an Earth satellite.** L. Blitzer. *Amer. J. Phys.*, **27**, 634–45 (*Dec.*, 1959). Investigates the effect of the Sun and Moon on the orbit of a near satellite of Earth. The principal effect is a precession of the orbit plane about the pole of the ecliptic, about 10^{-4} of that due to Earth's oblateness.

(846) **On the numerical computation of free trajectories of a lunar space vehicle.** J. M. J. Kooy and J. Berghuis. *Astronautica Acta*, **6** (2–3), 115–43 (1960). A three-dimensional orbit was worked out, in which the vehicle approaches the Moon to within about 11,000 km., and so arrives at a position from which the hidden lunar hemisphere can be observed. In this example the launcher site chosen was on the equator. In a subsequent investigation the launcher site was chosen along a northern latitude. The effects of the application of a retro-rocket in the vicinity of the Moon have also been explored. Orbits planned to hit the Moon, and also to circumnavigate the Moon and return to Earth have been obtained; in all these cases solar and lunar disturbances have been taken into account. In addition, the possibility of launching a Moon-satellite has also been examined and a corresponding orbit computed. It appeared that the Kepler motion of such a Moon satellite (with respect to a selenocentric system of reference, and not rotating with respect to the celestial sky) is strongly influenced by the combined terrestial and solar disturbances. (9 *refs.*)

(847) **The theory of correctional manoeuvres in interplanetary space.** D. F. Lawden and R. S. Long. *Astronautica Acta*, **6** (1), 48–60 (1960). The computation of correctional manoeuvres is shown to be independent of all small perturbing forces, so that the rocket track may be supposed to be a Keplerian arc which it follows under the attraction of the Sun alone. The calculation can be reduced to a substitution of the observed divergence from a precomputed track into given formulae, the coefficients in which can all be determined prior to departure and stored in a computer.

(848) **Design and evaluation of a re-entry guidance system.** H. Reismann and J. S. Pistiner. *Astronautica Acta*, **6** (2–3), 79–114 (1960). Design and analysis of a fully automatic re-entry guidance system that will permit safe recovery of the vehicle within 0·02 n.miles. (1 σ) of a preselected point on the Earth's surface (neglecting winds and terminal dispersions due to parachute landing) for initial re-entry conditions achievable with existing equipments. (17 *refs.*)

(849) **The orbits of cosmic rockets towards the Moon.** L. I. Sedov. *Astronautica Acta*, **6** (1), 16–31 (1960).
The applicability of rockets for investigation on the invisible side of the Moon is discussed. The characteristics of a set of trajectories lying around a central trajectory are studied with the aid of new methods. A six-parameter set of trajectories is transformed into a two-parameter set. The peculiarities of certain trajectories are given with respect to the possibility of photographing the invisible side of the Moon and to favourable conditions for receiving radio signals from that region. The observations and the fundamental results of measurements of three Soviet cosmic rockets on the hitherto unknown side of the Moon were obtained in 1959. Photographing the invisible side and transmitting radio signals to the Earth by means of Automatic Interplanetary Stations were both successful.

(850) **The motion of an artificial satellite in the vicinity of the critical inclination.** G. Hori. *Astronom. J.*, **65** (5), 291–300 (*June*, 1960). Using method of canonical transformations the motion of a satellite near the critical inclination is studied. The solution gives the motion of the perigee in terms of libration, circulation and a transitional type of motion.

(851) **Observing the satellites.** M. Melin. *Sky and Telescope*, **20** (1), 19 (*July*, 1960). Descriptions of *Sputnik IV* and *Midas II*.

(852) **Long focus camera for determining coordinates of faint artificial Earth satellites.** M. K. Abele. *Soviet Astronomy*, **4** (1), 134–40 (*July–Aug.*, 1960). [Translation from *Astronomicheskii Zhurnal*, **37** (1), 140–6 (*Jan.–Feb.*, 1960)].

(853) **Periodic drag perturbations of artificial satellites.** I. G. Izsak. *Astronom. J.*, **65** (6), 354–7 (*Aug.*, 1960). Fourier analysis of differential equations for orbital elements, with approximation for mean density of atmosphere.

(854) **Observing the satellites.** M. Melin. *Sky and Telescope*, **20** (2), 84–7 (*Aug.*, 1960). Description of *Transit II–A* and Saturn rocket programme.

(855) **Observing the satellites.** M. Melin. *Sky and Telescope*, **20** (3), 130–1 (*Sept.*, 1960). List of orbital and structural characteristics of all 28 satellites aloft on 1 Aug., 1960.

(856) **Observing the satellites.** M. Melin. *Sky and Telescope*, **20** (4), 200–3 (*Oct.*, 1960). *Echo I* and recovery from orbit of several satellites are described.

7—PROPULSION

.1 *General*

(857) **Jets and rockets and how they work.** W. P. Gottlieb. $2.95, *Garden City Books, N.Y.* $3.49, *Doubleday, Toronto* (1959). Juvenile.

(858) **Astronautics and propulsion.** K. A. Ehricke. *I.R.E. Trans. on Military Electronics*, **MIL-3** (2), 58–64 (*April*, 1959).

(859) **Problems of space propulsion.** *Aeroplane*, **99**, 691 (18 *Nov.*, 1960).

.3 *Chemical Rockets*

GENERAL

[*See also* abstract no. 908]

(860) **The rocket, ultimate propulsion.** A. Ducrocq. *Sciences et Avenir*, **131** (*Jan.*, 1958). (*In French.*)

(861) **Liquid versus solid propellant rockets.** G. S. Sutherland. *Soc. Automot. Engrs. J.*, **66**, 48–54 (*July*, 1958).

(862) **Problems of intercontinental ballistic missile propulsion.** H. Verdier. *Tech. Sci. Aeronaut.*, 1958, 164–72 (*Aug.*, 1958). (*In French.*)

(863) **Aerojet's bet on rockets pays off.** R. M. Loebelson. *Space-Aeronautics*, **30** (3), 16–7, 204 (*Sept.*, 1958).

(864) **Rocket handbook for amateurs.** C. M. Parkin, ed. $5.95, *Day, N.Y.* $5.75, *Longmans, Toronto* (1959).

(865) **Reply to Crocco's criticism of the Zucrow-Osborn paper.** M. J. Zucrow and J. R. Osborn. *ARS J.*, **29**, 221–2 (*March*, 1959). (17 *refs.*) Comment on **Comments on the Zucrow-Osborn paper on combustion oscillations.** L. Crocco. *Jet. Prop.*, **28**, 843–4 (*Dec.*, 1958).

(866) **Comments on "Exhaust nozzle contour for maximum thrust."** R. W. Fanselau. *ARS J.*, **29**, 456–7 (*June*, 1959). For original paper see *ARS J.*, **28**, 377–82 (*June*, 1958).

(867) **How to handle 24-megaton thrust?** C. J. Hamlin. *Missiles and Rockets*, **5** (27), 16–18 (29 *June*, 1959).

(868) **Building rocket engines for the country's defense.** C. O. Herb. *Machinery*, **65**, 122–9 (*July*, 1959).

(869) **Rocket power; new pipeline tool.** J. Joseph. *Gas*, **35**, 151–3 (*Oct.*, 1959).

(870) **Rocket engines and their design problems.** *Bristol-Siddeley J.*, **1** (4), 79–83 (1960).

(871) **Infrared spectral and total teleradiometer.** A. G. DeBell. *Optical Soc. Amer. Paper WB15.* (*Oct.*, 1960). This infrared instrument (known as *IRSATT*) was designed for the study of rocket engine exhaust plumes and is able to distinguish between spectral and temporal variations during a spectral scan, and to locate (and record by means of a boresighted fiducial camera) the exact location in a heterogeneous source at which the spectral measurements are being made.

(872) **Rocketdyne round-up.** *Flight*, **78**, 773, 778, 857 (18 and 25 *Nov.*, 1960).

.31 SOLID-PROPELLENT ROCKETS

(873) **Rocket engines with two thrust levels.** R. S. Newman *Missili*, **1**, 51–3 (*Feb.*, 1959). (*In Italian.*) *See also* **Why not dual.**

thrust engines? *Astronautics*, **3** (3), 26–8, 48–9 (*March*, 1958).
(874) **A complication in solid rockets: how to direct the nozzle.** N. L. Baker. *Alata*, **15** (167), 76–8 (*May*, 1959). (*In Italian.*)
(875) **Rocket readiness.** J. W. Wiggins. *Ordnance*, **43**, 1010–12 (*May–June*, 1959). Solid motors.

.32 Liquid-Propellent Rockets

[*See also* abstract no. 771]

(876) **Problems of heat transfer in rocket motors. H. Ziebland.** *Rev. Asoc. Argent. Interplanet.*, **3** (12), 9–21 (*July–Sept.*, 1956). (*In Spanish.*) [Translated by P. M. Viarnés from *J.B.I.S.*, **14**, 248–64 (*Sept.–Oct.*, 1955).]
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33 Propellents

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12—SPACE LAW; SOCIOLOGY

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13—MISCELLANEOUS

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(976) **Satellite centre.** *Flight*, **78**, 664–5 (28 *Oct.*, 1960). History and organisation of the Goddard Spaceflight Center.

BOOK REVIEW

The Exploration of Space. Edited by Robert Jastrow. 10 × 7 in. Pp. vi + 160, illustrated. 1960. New York: Macmillan Co. ($5.50); London: Macmillan (38s. 6d.).

This excellent and most readable book is the proceedings of a Symposium on Space Physics held in Washington, 29–30 April, 1959, and sponsored jointly by the U.S. National Academy of Sciences, the National Aeronautics and Space Administration, and the American Physical Society. The papers were first published in the *Journal of Geophysical Research* for August and November, 1959.

The objectives of the symposium, according to the editor, "were (1) to awaken the interest of the scientific community in the problems of space research; (2) to present an estimate of our present and future capabilities for space exploration, including the study of the upper atmosphere, the exploration of the Moon and near-by planets, and the observation of the Sun and stars from orbiting space platforms; (3) to acquaint the experimentalist with existing instrumentation in space physics and to challenge his ingenuity in the construction of new apparatus." The participants were of the highest calibre and their papers are completely authoritative at the semi-technical level.

The papers presented range from accounts of work done (J. A. Van Allen on study of the radiation belts, N. C. Christofilos on the Argus experiment, H. C. Urey on analysis of meteorites) to the discussion of more-or-less speculative hypotheses (T. Gold on the ejection of plasma from the Sun and the influence on it of magnetic fields in space, E. Parker on the solar corona extending into space as a solar wind); from reviews of present knowledge (G. P. Kuiper on the Moon, G. de Vaucoleurs on Mars and Venus, R. Jastrow on the upper atmospheres of the Earth, Moon, and planets) to a review of what is not known in one area (F. L. Whipple on solid particles, smaller than planets, in orbit round the Sun); from an account of astronomical observations already made from rockets (H. Friedman) to a consideration of those that might be made from satellites and space vehicles (L. Goldberg), together with details of the scientific apparatus currently being prepared for carriage in satellites (J. W. Townsend) and the production plans for the rocket vehicles to take them into space (H. E. Newell).

The papers on engineering and instrumentation state clearly the functions aimed at, the design criteria and priorities, and, where possible, the expected development times. The physical and astronomical papers, with even greater clarity and without exception, differentiate what is known from what is hypothesis, and indicate with precision the experiments required to provide the missing information or to decide between antagonistic theories. Most of the papers are followed by pertinent questions and answers, and three round-table discussions are valuable in themselves, with significant contributions on a variety of topics (*e.g.* concerning Kozyrev's observations of a type of volcanic activity on the Moon).

It is not possible to judge whether the book will succeed in awakening the interest of the whole scientific community, though it certainly should. But for physicists, chemists, and related workers, the aims seem to have been admirably achieved. And although the detailed projects discussed by the several speakers would seem to represent a programme of perhaps 10 years' work, yet still Dr. Newell, speaking on behalf of N.A.S.A., appeals for more ideas, mentions the fellowship grants available to support them, and gives details of how to apply for such grants.

D. ROSEN.

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